Shock interactions for the Burgers-Hilbert equation

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\textbf{ABSTRACT}
This paper provides an asymptotic description of a solution to the Burgers-Hilbert equation in a neighborhood of a point where two shocks interact. The solution is obtained as the sum of a function with $H^2$ regularity away from the shocks plus a corrector term having an asymptotic behavior like $|x| \ln |x|$ close to each shock. A key step in the analysis is the construction of piecewise smooth solutions with a single shock for a general class of initial data.

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1. Introduction

Consider the balance law obtained from Burgers’ equation by adding the Hilbert transform as a source term

$$u_t + \left( \frac{u^2}{2} \right)_x = H[u]. \quad (1.1)$$

This equation was derived in \cite{1} as a model for nonlinear waves with constant frequency. Here the nonlocal source term

$$H[f](x) = \lim_{\varepsilon \to 0^+} \frac{1}{\pi} \int_{|y| > \varepsilon} \frac{f(x-y)}{y} \, dy$$

denotes the Hilbert transform of a function $f \in L^2(\mathbb{R})$. It is well known \cite{2} that $H$ is a linear isometry from $L^2(\mathbb{R})$ onto itself. Given any initial data

$$u(0, \cdot) = \bar{u}(\cdot) \quad (1.2)$$

with $\bar{u} \in H^2(\mathbb{R})$, the local existence and uniqueness of solutions to (1.1) was proved in \cite{3}, together with a sharp estimate on the time interval where this solution remains smooth. For a general initial data $\bar{u} \in L^2(\mathbb{R})$, the global existence of entropy weak solutions to (1.1) was proved in \cite{4}, together with a partial uniqueness result. We remark that the well-posedness of the Cauchy problem for (1.1) remains a largely open question.

More recently, piecewise continuous solutions with a single shock have been constructed in \cite{5}. As shown in Figure 1, these solutions have the form
\[ u(t, x) = w(t, x - y(t)) + \varphi(x - y(t)), \tag{1.3} \]

where \( y(t) \) denotes the location of the shock at time \( t \), and \( w(t, \cdot) \in H^2([-\infty, 0] \cup [0, +\infty]) \) for all \( t \geq 0 \). Moreover, \( \varphi \) is a fixed function with compact support, describing the asymptotic behavior of the solution near the shock. It is smooth outside the origin and satisfies

\[ \varphi(x) = \frac{2}{\pi} |x| \ln |x| \quad \text{for} \quad |x| \leq 1. \tag{1.4} \]

Remarkably, this “corrector term” \( \varphi \) is universal, i.e., it does not depend on the particular solution of (1.1). The same analysis applies to solutions with finitely many, non-interacting shocks. In addition, the local asymptotic behavior of a solution up to the time when a new shock is formed was investigated in [6].

The aim of the present note is to describe the asymptotic behavior of a solution in a neighborhood of a point where two shocks interact. Calling \( T > 0 \) the time when the interaction takes place, our analysis splits into two parts. We first describe the behavior of the solution as \( t \to T^- \), i.e., as the two shocks approach each other. In a second step, to construct the solution for \( t > T \), we solve a Cauchy problem with initial data given at \( t = T \).

As it turns out, the profile \( u(T, \cdot) \) is not “well prepared,” in the sense that it cannot be written in the form (1.3). To explain the difficulty, we recall that the solutions constructed in [5] had initial data of the form

\[ u(0, x) = \tilde{w}(x - y_0) + \varphi(x - y_0), \tag{1.5} \]

for some \( \tilde{w} \in H^2(\mathbb{R}\setminus\{0\}) \) and \( y_0 \in \mathbb{R} \). These data are “well prepared,” in the sense that they already contain the corrector term \( \varphi \). A natural class of initial data, not considered in [5], is

\[ u(0, x) = \tilde{w}(x - y_0) \quad \text{with} \quad \tilde{w} \in H^2(\mathbb{R}\setminus\{0\}), \quad y_0 \in \mathbb{R}. \tag{1.6} \]

By assumption, at time \( t = 0 \) the derivative \( u_x(0, x) = \tilde{w}_x(x - y_0) \) is piecewise continuous and uniformly bounded. However, in the solution to (1.1), (1.6), at each time \( t > 0 \) we expect that \( u_x(t, x) \to \pm \infty \) as \( x \to y(t) \mp \). For this reason, the local construction of this solution requires a careful analysis. A more general class of initial data, containing both (1.5) and (1.6), as well as all profiles \( u(T, \cdot) \) emerging from our shock interactions, will be studied in Section 2.

We recall here the definition of entropy weak solutions used in [4].

**Definition 1.1.** By an entropy weak solution of (1.1)–(1.2) we mean a function \( u \in L^1_{\text{loc}}([0, \infty) \times \mathbb{R}) \) with the following properties.
(i) The map $t \mapsto u(t, \cdot)$ is continuous with values in $L^2(\mathbb{R})$ and satisfies the initial condition (1.2).

(ii) For any $k \in \mathbb{R}$ and every nonnegative test function $\phi \in C^1_c([0, \infty[ \times \mathbb{R})$ one has

$$\int \int \left[ u - k |\phi_t + \left( \frac{u^2 - k^2}{2} \right) \text{sign}(u-k) \phi_x + H[u(t)](x) \text{sign}(u-k) \phi \right] \, dx \, dt \geq 0. \tag{1.7}$$

The present paper will be concerned with a more regular class of solutions, which are piecewise continuous and can be determined by integrating along characteristics. These correspond to the “broad solutions” considered in [7,8]. Throughout the sequel, the upper dot denotes a derivative w.r.t. time.

**Definition 1.2.** An entropy weak solution $u = u(t,x)$ of (1.1)–(1.2), defined on the interval $t \in [0,T]$, will be called a **piecewise regular solution** if there exist finitely many shock curves $y_1(t), \ldots, y_n(t)$ such that the following holds.

(i) For each $t \in [0,T]$, one has $u(t, \cdot) \in H^2(\mathbb{R}\setminus\{y_1(t), \ldots, y_n(t)\})$.

(ii) For each $i = 1, \ldots, n$, the Rankine-Hugoniot conditions hold:

$$u_i^-(t) = u(t,y_i(t)-) > u(t,y_i(t)+) = u_i^+(t), \quad \dot{y}_i(t) = \frac{u_i^-(t) + u_i^+(t)}{2}. \tag{1.8}$$

(iii) Along every characteristic curve $t \mapsto x(t)$ such that

$$\dot{x}(t) = u(t,x(t)), \tag{1.10}$$

one has

$$\frac{d}{dt} u(t,x(t)) = H[u](x(t)). \tag{1.11}$$

In the above setting, the Hilbert transform of the piecewise regular function $u(t, \cdot)$ can be computed using an integration by parts:

$$H[u(t)](x) = \frac{1}{\pi y} \int_{-\infty}^{\infty} u_x(t,y) \ln |x-y| \, dy + \frac{1}{\pi} \sum_{i=1}^{n} \left[ u_i^+(t) - u_i^-(t) \right] \ln |x-y_i(t)|. \tag{1.12}$$

The remainder of the paper is organized as follows. In **Section 2** we state a local existence and uniqueness theorem for solutions to (1.1), valid for a class of initial data containing one single shock, but more general than in [5]. Toward the proof of **Theorem 2.1**, **Section 3** develops various a priori estimates, while in **Section 4** the local solution is constructed as a limit of a convergent sequence of approximations. As in [5], these are obtained by iteratively solving a sequence of linearized problems.

In the second part of the paper we study solutions of (1.1) with two shocks, up to the time of interaction. In **Section 5** we perform some preliminary computations, motivating a particular form of the corrector term. In **Section 6** we state and prove the second main result of the paper, **Theorem 6.1**, providing a detailed description of
solutions up to the interaction time. This is achieved by a change of both time and space coordinates, so that the two shocks are located at the two points

\[ x_1(t) = t < 0 = x_2(t), \]

and interact at time \( t = 0 \). Our analysis shows that, at the interaction time, the solution profile contains a single shock and lies within the class of initial data covered by Theorem 2.1. Combining our two theorems, one thus obtains a complete description of the solution to (1.1) in a neighborhood of the interaction time.

2. Solutions with one shock and general initial data

Consider a piecewise regular solution of the Burgers-Hilbert equation (1.1), with one single shock. By the Rankine-Hugoniot condition, the location \( y(t) \) of the shock at time \( t \) satisfies

\[ \dot{y}(t) = \frac{u^-(t) + u^+(t)}{2}, \quad u^\pm(t) = \lim_{x \to y(t) \pm} u(t, x). \] (2.1)

As in [5], we shift the space coordinate, replacing \( x \) with \( x - y(t) \), so that in the new coordinate system the shock is always located at the origin. In these new coordinates, (1.1) takes the form

\[ u_t + \left( u - \frac{u^-(t) + u^+(t)}{2} \right) u_x = H[u]. \] (2.2)

In [5], given a “well prepared” initial data (1.5), a unique piecewise smooth entropy solution to (2.2) of the form

\[ u(t, x) = w(t, x) + \frac{2\eta(x)}{\pi} \cdot |x| \ln |x|, \quad t > 0 \]

was constructed. Here \( w(t, \cdot) \in H^2(\mathbb{R}\setminus\{0\}) \), while \( \eta \in C^\infty(\mathbb{R}) \) is an even cutoff function, satisfying

\[ \begin{cases} 
\eta(x) = 1 & \text{if } |x| \leq 1, \\
\eta(x) = 0 & \text{if } |x| \geq 2, \\
\eta'(x) \leq 0 & \text{if } x \geq 0. 
\end{cases} \] (2.3)

For future use, it will be convenient to introduce the function

\[ \phi(x, b) = \frac{2\eta(x)}{\pi} \cdot [(|x| + b) \ln (|x| + b) - b \ln b], \quad x \in \mathbb{R}, \ b \geq 0. \] (2.4)

Observe that

\[ \phi(0, b) = 0 \quad \text{for all } \ b \geq 0. \] (2.5)

Our main goal in this section is to solve the Cauchy problem for (2.2) with initial data

\[ u(0, x) = \bar{w}(x) + \bar{\phi}(x), \] (2.6)

where
\[ \bar{w} \in H^2(\mathbb{R} \setminus \{0\}), \quad \phi(x) = (c_1 \cdot \chi_{]-\infty,0[} + c_2 \cdot \chi_{]0, +\infty[}) \cdot \phi(x,0), \] (2.7)

for some constants \( c_1, c_2 \in \mathbb{R} \). Note that this reduces to (1.5) in the case \( c_1 = c_2 = 1 \).

To handle the more general initial data (2.6)–(2.7), we write the solution of (2.2) in the form
\[ u(t, x) = w(t, x) + \varphi^{(w)}(t, x), \] (2.8)
where the corrector term \( \varphi^{(w)}(t, x) \) now depends explicitly on time \( t \) and on the strength of the jump
\[ \sigma^{(w)}(t) = w^-(t) - w^+(t), \quad w^\pm(t) = w(t, 0 \pm). \] (2.9)

To make an appropriate guess for the function \( \varphi^{(w)} \), we observe that, by (1.12), (2.2) can be approximated by the simpler equation
\[ u_t + u \cdot u_x = \frac{w^-(t) + w^+(t)}{2}, \] (2.10)
Indeed, we expect that the solutions of (2.2) and (2.10) with the same initial data will have the same asymptotic structure near the origin. Their difference will lie in the more regular space \( H^2(\mathbb{R} \setminus \{0\}) \). With this in mind, we thus make the ansatz
\[ \varphi^{(w)}(t, x) \approx \phi(x, 0) + \left( (c_1 - 1) \cdot \chi_{]-\infty,0[} + (c_2 - 1) \cdot \chi_{]0, +\infty[} \right) \cdot \phi\left(x, \frac{\sigma^{(w)}(t)t}{2}\right). \] (2.11)

Inserting (2.8) into (2.2), we obtain an equation for the remaining component \( w(t, \cdot) \). Namely
\[ w_t + a(t, x, w) \cdot w_x = F(t, x, w), \] (2.12)
where \( a \) and \( F \) are given by
\[ a(t, x, w) = w(t, x) + \varphi^{(w)}(t, x) - \frac{w^-(t) + w^+(t)}{2}, \] (2.13)
\[ F(t, x, w) = H[\varphi^{(w)}](t, x) - \varphi^{(w)} \cdot \varphi_x^{(w)}(t, x) \]
\[ + \left( H[w](t, x) - \left[ \varphi_t^{(w)}(t, x) + \left( w(t, x) - \frac{w^-(t) + w^+(t)}{2} \right) \cdot \varphi_x^{(w)}(t, x) \right] \right). \] (2.14)

We observe that, in the present case of a solution with a single shock, by (2.5) the entropy admissibility condition (1.8) reduces to
\[ w^-(t) > w^+(t). \] (2.15)
Moreover, Definition 1.2 is satisfied provided that, along every characteristic curve \( t \mapsto x(t; t_0, x_0) \neq 0 \) obtained by solving
\[ \dot{x}(t) = a(t, x, w), \quad x(t_0) = x_0, \] (2.16)
one has
\[ w(t_0, x_0) = \bar{w}(x(0; t_0, x_0)) + \int_0^{t_0} F(t, x(t; t_0, x_0), w(t, x(t; t_0, x_0))) \, dt. \] (2.17)

The first main result of this paper provides the existence and uniqueness of an entropic solution, locally in time.

**Theorem 2.1.** For every \( \bar{w} \in H^2(\mathbb{R} \setminus \{0\}) \) satisfying \( \bar{w}(0-) - \bar{w}(0+) > 0 \) and every \( c_1, c_2 \in \mathbb{R} \), the Cauchy problem for the Burgers-Hilbert equation (1.1), with initial condition as in (2.6)–(2.7), admits a unique piecewise regular solution defined for \( t \in [0, T] \), for some \( T > 0 \) sufficiently small, depending only on \( M_0, \delta_0, c_1, \) and \( c_2 \).

The solution to the equivalent (2.12) will be obtained as a limit of a sequence of approximations. Namely, consider a sequence of linear approximations constructed as follows. As a first step, define

\[ w_1(t, x) = \bar{w}(x) \quad \text{for all} \quad t \geq 0, \quad x \in \mathbb{R}. \] (2.18)

By induction, let \( w_n \) be given. We define \( w_{n+1} \) to be the solution of the linear, non-homogeneous Cauchy problem

\[ w_t + a(t, x, w_n) \cdot w_x = F(t, x, w), \quad w(0, \cdot) = \bar{w}(x). \] (2.19)

The induction argument requires three steps:

(i) Existence and uniqueness of solutions to each linear problem (2.19).
(ii) A priori bounds on the strong norm \( \|w_n(t)\|_{H^1(\mathbb{R} \setminus \{0\})} \), uniformly valid for \( t \in [0, T] \) and all \( n \geq 1 \).
(iii) Convergence in a weak norm. This will follow from the bound

\[ \sum_{n \geq 2} \|w_n(t) - w_{n-1}(t)\|_{H^1(\mathbb{R} \setminus \{0\})} < \infty. \] (2.20)

These steps will be worked out in the next two sections.

**3. Preliminary estimates**

To achieve the above steps (i)–(iii), we establish in this section some key estimates on the right hand side of (2.19), by splitting it into three parts:

\[ F(t, x, w) = A^{(w)}(t, x) + B^{(w)}(t, x) - C^{(w)}(t, x), \] (3.1)

where

\[ A^{(w)} = \mathbf{H} \left[ \phi^{(w)} - \phi^{(w)} \phi_x^{(w)} \right], \quad B^{(w)} = \mathbf{H}[w] - \left( w - \frac{w^- + w^+}{2} \right) \cdot \phi_x(x, 0), \] (3.2)

\[ C^{(w)} = \phi_t^{(w)} + \left( w - \frac{w^- + w^+}{2} \right) \cdot \phi_x \left( x, \sigma^{(w)}(t) \cdot \frac{t}{2} \right) \cdot \left( (c_1 - 1) \cdot \mathcal{X}_{[0, +\infty]} + (c_2 - 1) \cdot \mathcal{X}_{[0, +\infty]} \right). \] (3.3)

Consider the function

\[ g_b(x) = \chi_{[0, \infty]}(x) \cdot \phi(x, b), \quad x \in \mathbb{R}, \quad b \geq 0, \] (3.4)
where $\phi(x, b)$ is given by (2.4). For every $b \in [0, \frac{1}{2e}]$ one checks that the function $g_b \in C^\infty(\mathbb{R} \setminus \{0\}) \cap C(\mathbb{R})$ is negative and decreasing on the open interval $]0, \frac{1}{2e}[$. Moreover, it satisfies

$$\supp(g_b) \subseteq [0, 2], \quad |g_b(z)| \leq |z \ln |z|| \quad \text{for all } z \in \left[0, \frac{1}{2e}\right]. \quad (3.5)$$

The next lemma provides some bounds on the Hilbert transform of $g_b$. As usual, by the Landau symbol $\mathcal{O}(1)$ we shall denote a uniformly bounded quantity.

**Lemma 3.1.** For every $0 \leq b \leq \frac{1}{2e}$ and $|x| \leq \frac{1}{2e}$ one has

$$\begin{cases}
|\mathbf{H}[g_b](x)| &\leq \mathcal{O}(1), \\
\left|\frac{d^2}{dx^2} \mathbf{H}[g_b](x)\right| &\leq \mathcal{O}(1) \cdot \ln^2 |x|, \\
\left|\frac{d}{dx} \mathbf{H}[g_b](x)\right| &\leq \mathcal{O}(1) \cdot \frac{\ln |x|}{x^2}.
\end{cases} \quad (3.6)$$

Moreover, for every $\delta > 0$ sufficiently small one has

$$\|\mathbf{H}[g_b](\cdot)\|_{H^p(\mathbb{R} \setminus [-\delta, \delta])} \leq \mathcal{O}(1) \cdot \delta^{-2/3}, \quad \|\mathbf{H}[g_b'](\cdot)\|_{H^p(\mathbb{R} \setminus [-\delta, \delta])} \leq \mathcal{O}(1) \cdot \delta^{-7/4}. \quad (3.7)$$

**Proof.** Fix $b \in [0, \frac{1}{2e}]$. By (1.12), one has

$$\mathbf{H}[g_b](x) = \frac{1}{\pi} \int_0^2 g_b'(y) \cdot \ln |x - y| \, dy.$$ 

Two cases are considered:

**Case 1:** If $-\frac{1}{2e} < x < 0$ then we have the estimates

$$|\mathbf{H}[g_b](x)| = \frac{1}{\pi} \left| \int_0^2 g_b'(y) \cdot \ln (y - x) \, dy \right| = \frac{1}{\pi} \left| \int_{|x|}^{2+|x|} g_b(x + z) \ln z \, dz \right|$$

$$= \frac{1}{\pi} \left| \int_{|x|}^{2+|x|} \frac{g_b(x + z)}{z} \, dz \right| \leq \mathcal{O}(1) \cdot \left( \int_{|x|}^{2+|x|} |\ln z| \, dz + 1 \right) \leq \mathcal{O}(1),$$

$$\left|\frac{d}{dx} \mathbf{H}[g_b](x)\right| = \frac{1}{\pi} \left| \int_0^2 g_b'(y) \, dy \right| = \frac{1}{\pi} \left| \int_{|x|}^{2+|x|} \frac{g_b(x + z)}{z} \, dz \right|$$

$$= \frac{1}{\pi} \left| \int_{|x|}^{2+|x|} \frac{g_b(x + z)}{z^2} \, dz \right| = \mathcal{O}(1) \cdot \left( \int_{|x|}^{2+|x|} |\ln z| \, dz + 1 \right) \leq \mathcal{O}(1) \cdot \ln^2 |x|,$$

and similarly

$$\left|\frac{d^2}{dx^2} \mathbf{H}[g_b](x)\right| \leq \mathcal{O}(1) \cdot \frac{\ln |x|}{x}, \quad \left|\frac{d^3}{dx^3} \mathbf{H}[g_b](x)\right| \leq \mathcal{O}(1) \cdot \frac{\ln |x|}{x^2}.$$
Case 2: If $0 < x < \frac{1}{2e^2}$, then we split $H[g_b](x)$ into three parts as follows:

$$H[g_b](x) = \frac{1}{\pi} \cdot \left( \int_0^{x/2} g_b'(y) \ln (x - y) \, dy + \text{p.v.} \int_{x/2}^{3x/2} g_b'(y) \ln |y - x| \, dy \right)$$

$$+ \frac{1}{\pi} \cdot \int_{3x/2}^x g_b'(y) \ln (y - x) \, dy = \frac{1}{\pi} \cdot (I_1 + I_2 + I_3).$$

We first estimate

$$|I_1(x)| = \left| \int_0^{x/2} g_b'(y) \ln (x - y) \, dy \right| \leq O(1) \cdot \left| \int_0^{x/2} g_b'(y) \, dy \right| \cdot |\ln x| \leq O(1) \cdot x \ln^2 x,$$

$$|I_1'(x)| = \left| \int_0^{x/2} \frac{g_b'(y)}{x - y} \, dy + \frac{1}{2} \cdot g_b'(\frac{x}{2}) \ln \left( \frac{x}{2} \right) \right| \leq O(1) \cdot \ln^2 x,$$

and similarly

$$|I_1''(x)| \leq O(1) \cdot \frac{\ln x}{x}, \quad |I_1'''(x)| \leq O(1) \cdot \frac{\ln x}{x^2}.$$

By a similar argument, one obtains

$$|I_3(x)| \leq O(1), \quad |I_3'(x)| = \left| \int_{3x/2}^x \frac{g_b'(y)}{y - x} \, dy + \frac{3}{2} \cdot g_b'(\frac{3x}{2}) \cdot \ln \left( \frac{x}{2} \right) \right| \leq O(1) \cdot \ln^2 x,$$

and

$$\left\{ \begin{array}{l}
|I_3''(x)| \leq \left| \int_{3x/2}^x \frac{g_b'(y)}{(y - x)^2} \, dy \right| + O(1) \cdot \frac{\ln x}{x} \leq O(1) \cdot \frac{\ln x}{x}, \\
|I_3'''(x)| \leq \left| \int_{3x/2}^x \frac{g_b'(y)}{(y - x)^3} \, dy \right| + O(1) \cdot \frac{\ln x}{x^2} \leq O(1) \cdot \frac{\ln x}{x^2}.
\end{array} \right.$$

Finally, using the fact that $g_b'$ is concave, we obtain

$$|I_2(x)| = \left| \lim_{\varepsilon \to 0^+} \int_{x/2}^{x-\varepsilon} g_b'(y) \ln (x - y) \, dy + \int_{x+\varepsilon}^{3x/2} g_b'(y) \ln (y - x) \, dy \right|$$

$$= \lim_{\varepsilon \to 0^+} \int_{x/2}^{x/2} \left[ g_b'(x - z) + g_b'(x + z) \right] \cdot \ln z \, dz \leq 2 |g_b'(x)| \cdot \int_{x/2}^{x/2} \ln z \, dz \leq O(1),$$

$$|I_2'(x)| = \left| \lim_{\varepsilon \to 0^+} \int_{x/2}^{x/2} \left[ g_b'''(x - z) + g_b''(x + z) \right] \ln z \, dz + \frac{1}{2} \left[ g_b'(x/2) + g_b'(3x/2) \right] \cdot \ln (x/2) \right|$$

$$\leq O(1) \cdot \left( |g_b''(x/2)| \cdot \int_{x/2}^{x/2} \ln z \, dz + \ln^2 x \right) \leq O(1) \cdot \ln^2 x,$$
and
\[
\begin{align*}
|P'_2(x)| &\leq \lim_{\varepsilon \to 0+} \int^x_{\varepsilon} \left[ g''_b(x-z) + g''_b(x+z) \right] \ln z dz + \mathcal{O}(1) \cdot \frac{\ln x}{x} \leq \mathcal{O}(1) \cdot \frac{\ln x}{x}, \\
|P''_2(x)| &\leq \lim_{\varepsilon \to 0+} \int^x_{\varepsilon} \left[ g''_b(x-z) + g''_b(x+z) \right] \ln z dz + \mathcal{O}(1) \cdot \frac{\ln x}{x^2} \leq \mathcal{O}(1) \cdot \frac{\ln x}{x^2}.
\end{align*}
\]

We thus achieve the same estimates as in Case 1, and this yields (3.6).

Finally, the function $g_b$ is continuous with compact support and smooth outside the origin. Therefore, the Hilbert transform $H[g_b]$ is smooth outside the origin. As $|x| \to \infty$, one has
\[
\begin{align*}
H[g_b](x) &= \mathcal{O}(1) \cdot |x|^{-1}, \quad \frac{d^k}{dx^k} (H[g_b])(x) = \mathcal{O}(1) \cdot x^{-(k+1)}, \quad k = 1, 2, 3.
\end{align*}
\]
Thus, (3.6) yields (3.7).

\hfill \Box

**Remark 3.1.** For every $0 < b \leq \frac{1}{2\pi}$, one has
\[
\frac{d}{db} g_b(x) = \frac{2\eta(x)}{\pi} [\ln (x + b) - \ln (b)] \quad \text{for all } x > 0.
\]
Since
\[
|\ln (x + b) - \ln (b)| \leq \frac{x}{b},
\]
the same arguments as used in the proof of **Lemma 3.1** yield that, for $0 < |x| \leq \frac{1}{2\pi}$,
\[
\begin{align*}
H \left[ \frac{d}{db} g_b \right](x) &= \mathcal{O}(1) \cdot \frac{1}{b}, \quad \frac{d}{dx} H \left[ \left( \frac{d}{db} g_b \right) \right](x) = \mathcal{O}(1) \cdot \frac{\ln (x)}{b}, \\
\frac{d^2}{dx^2} H \left[ \left( \frac{d}{db} g_b \right) \right](x) &= \mathcal{O}(1) \cdot \frac{\ln (x)}{b^2}.
\end{align*}
\]
Moreover, for $\delta > 0$ sufficiently small,
\[
\begin{align*}
\left\| H \left[ \frac{d}{db} g_b \right] \right\|_{H^1(\mathbb{R} \setminus [-\delta, \delta])} &\leq \mathcal{O}(1) \cdot \frac{1}{b}, \quad \left\| H \left[ \frac{d}{db} g_b \right] \right\|_{H^2(\mathbb{R} \setminus [-\delta, \delta])} \leq \mathcal{O}(1) \cdot \frac{1}{b} \cdot \delta^{-2/3}.
\end{align*}
\]

The next lemma provides some a priori estimates on the function $F = F(t, x, w)$ introduced in (2.14).

**Lemma 3.2.** Let $w : [0, T] \times \mathbb{R} \to \mathbb{R}$ such that $w(t, \cdot) \in H^2(\mathbb{R} \setminus \{0\})$ for all $t \in [0, T]$,
\[
\|w(t, \cdot)\|_{H^2(\mathbb{R} \setminus \{0\})} \leq M_0, \quad \sigma^{(w)}(t) := w(t, 0-) - w(t, 0+) > 0.
\]
Moreover, assume that $0 < T < \frac{1}{4M_0}$ and that $\sigma^{(w)}(\cdot)$ is locally Lipschitz on $[0, T]$.
Then there exists a constant $C_1 > 0$, depending on $M_0$, $\delta_0$, $c_1$, and $c_2$ such that, for a.e. $t \in [0, T]$ and $|x| < \frac{1}{2\pi}$ one has
\[
\begin{aligned}
|F(t,x,w)| & \leq C_1 \cdot \left( (1 + M_0) \cdot |\ln t| + \frac{|\dot{\sigma}(w)(t)|}{\sigma(w)(t)} \cdot |x| \right), \\
|F_x(t,x,w)| & \leq C_1 \cdot \left( (1 + M_0) \cdot |x|^{-1/4} + \frac{|\dot{\sigma}(w)(t)|}{\sigma(w)(t)} \right).
\end{aligned}
\] (3.8)

Furthermore, for every \(\delta > 0\) sufficiently small
\[
\|F(t,x,w)\|_{H^2(\mathbb{R})} \leq C_1 \cdot \left[ \left( 1 + M_0 + \frac{|\dot{\sigma}(w)(t)|}{\sigma(w)(t)} \right) \cdot \delta^{-2/3} + (1 + M_0) \cdot |\ln t| \right].
\] (3.9)

**Proof.** According to (3.1), the function \(F\) can be decomposed as the sum of three terms, which will be estimated separately.

1. By the analysis in [5, Section 3], for every \((t,x) \in [0,T] \times [-\frac{1}{2\pi}, \frac{1}{2\pi}]\) one has
\[
\begin{aligned}
|B^{(w)}(t,x)| & \leq O(1) \cdot M_0, \\
|B_x^{(w)}(t,x)| & \leq O(1) \cdot M_0 \cdot |\ln |x||^2, \\
\|B^{(w)}(t,\cdot)\|_{H^2(\mathbb{R}\setminus[\delta,\delta])} & \leq O(1) \cdot M_0 \cdot \delta^{-2/3}.
\end{aligned}
\] (3.10)

2. Next, we estimate \(C^{(w)}(t,x)\). For every \(0 < x < \frac{1}{2\pi}\), we have
\[
C^{(w)}(t,x) = E^{(w)}_2(t) + (c_2 - 1) \cdot \left[ \frac{\dot{\sigma}(w)(t)t}{2} + (w(t,x) - w(t,0+)) \right] \cdot \phi_x \left( x, \frac{\sigma^{(w)}(t)t}{2} \right),
\] (3.11)

where we define
\[
E^{(w)}_2(t) = \frac{1 - c_2}{2} \cdot \phi_x \left( \frac{\sigma^{(w)}(t)t}{2}, 0 \right) \cdot \left( \dot{\sigma}(w)(t)t + \sigma^{(w)}(t) \right).
\]

Since \(\|w(t,\cdot)\|_{H^2(\mathbb{R}\setminus\{0\})} \leq M_0\), one has \(|\sigma^{(w)}(t)| \leq 2M_0\),
\[
|C^{(w)}(t,0+)| = \left| \frac{1 - c_2}{2} \cdot \phi_x \left( \frac{\sigma^{(w)}(t)t}{2}, 0 \right) \cdot \sigma^{(w)}(t) \right| \leq O(1) \cdot (1 + M_0) \cdot |\ln t|,
\] (3.12)

and
\[
|C^{(w)}(t,x)| \leq O(1) \left( (1 + M_0) \cdot |\ln t| + \frac{|\dot{\sigma}(w)(t)|}{\sigma(w)(t)} \cdot |x| \right).
\]

Moreover, observing that
This leads to the estimates

\[
\begin{align*}
\left| C_x^{(w)}(t, x) \right| & \leq O(1) \cdot \left| \frac{\sigma^{(w)}(t)}{2} + (w(t, x) - w(t, 0)) \right| \cdot \phi_x \left( x, \frac{\sigma^{(w)}(t)}{2} \right), \\
\left| C_{xx}^{(w)}(t, x) \right| & \leq O(1) \cdot \left[ \left( M_0 + \frac{|\sigma^{(w)}(t)|}{|\sigma^{(w)}(t)|} \right) \cdot |x|^{-1} + |w_{xx}(t, x)| \cdot |\ln |x|| \right].
\end{align*}
\]  
(3.13)

we estimate

\[
\begin{align*}
\left| C_x^{(w)}(t, x) \right| & \leq O(1) \cdot \left( M_0 \cdot |x|^{-1/4} + \sigma^{(w)}(t) \right), \\
\left| C_{xx}^{(w)}(t, x) \right| & \leq O(1) \cdot \left[ \left( M_0 + \frac{|\sigma^{(w)}(t)|}{|\sigma^{(w)}(t)|} \right) \cdot |x|^{-1} + |w_{xx}(t, x)| \cdot |\ln |x|| \right].
\end{align*}
\]  
(3.14)

Similarly, for every \(-\frac{1}{2e} < x < 0\), we have

\[
\begin{align*}
C^{(w)}(t, x) = E_1^{(w)}(t) - (c_1 - 1) \cdot \left[ \frac{\sigma^{(w)}(t)}{2} + (w(t, x) - w(t, 0)) \right] \cdot \phi_x \left( x, \frac{\sigma^{(w)}(t)}{2} \right), \\
E_1^{(w)}(t) = \frac{1 - c_1}{2} \cdot \phi_x \left( \frac{\sigma^{(w)}(t)}{2}, 0 \right) \cdot \left( \sigma^{(w)}(t) + \sigma^{(w)}(t) \right).
\end{align*}
\]

This yields the same bounds as in (3.11)–(3.14). We thus conclude

\[
\| C^{(w)}(t, \cdot) \|_{H^2(\mathbb{R} \setminus [-\delta, \delta])} \leq O(1) \cdot \left[ \left( M_0 + \frac{|\sigma^{(w)}(t)|}{|\sigma^{(w)}(t)|} \right) \cdot \delta^{-1/2} + M_0 \cdot |\ln |t|| \right].
\]  
(3.15)

3. Finally, to obtain a bound on \( A^{(w)} \) we observe that, by (3.5),

\[
\left| \varphi^{(w)}(t, x) \right| \leq O(1) \cdot |x \ln |x||, \quad (t, x) \in [0, T] \times \left[ -\frac{1}{2e}, \frac{1}{2e} \right].
\]

This leads to the estimates

\[
\begin{align*}
\left| \varphi^{(w)} \varphi_x^{(w)} \right| & \leq O(1) \cdot |x|^{1/2}, \quad \left| \varphi^{(w)} \varphi_x^{(w)} \right| \leq O(1) \cdot |\ln |x||, \quad \left| \varphi^{(w)} \varphi_x^{(w)} \right| \leq O(1) \cdot |\ln |x||.
\end{align*}
\]

Thus,

\[
\| \varphi^{(w)}(t, \cdot) \varphi_x^{(w)}(t, \cdot) \|_{H^2(\mathbb{R} \setminus [-\delta, \delta])} \leq O(1) \cdot \delta^{-2/3}.
\]

On the other hand, if \( 0 < T < \frac{1}{4eM_0} \), then \( \sup_{t \in [0, T]} \sigma^{(w)}(t, t) \leq \frac{1}{2e} \) and Lemma 3.1 implies for all \( t \in [0, T] \) and \( |x| \leq \frac{1}{2e} \), that

\[
\begin{align*}
\left| H \left( \varphi^{(w)}(t, \cdot) \right) (x) \right| & \leq O(1), \quad \left| \frac{d}{dx} H \left( \varphi^{(w)}(t, \cdot) \right) (x) \right| \leq O(1) \cdot |\ln |x||, \quad (3.16)
\end{align*}
\]
\[ \frac{d^2}{dx^2} H \left[ \varphi^{(w)}(t, \cdot) \right] (x) \leq \mathcal{O}(1) \cdot \left| \frac{\ln |x|}{x} \right|, \quad \left\| H \left[ \varphi^{(w)}(t, \cdot) \right] \right\|_{H^2(\mathbb{R} \setminus [-\delta, \delta])} \leq \mathcal{O}(1) \cdot \delta^{-2/3}. \]

(3.17)

Therefore, combining (3.10)–(3.17), we obtain (3.8)–(3.9). This completes the proof.

Our third lemma estimates the change in the function \( F = F(t, x, w) \) as \( w(\cdot) \) takes different values. These estimates will play a key role in the proof of convergence of the approximations considered at (2.20).

**Lemma 3.3.** Let \( w_i : [0, T] \times \mathbb{R} \rightarrow \mathbb{R}, \ i = 1, 2 \) such that for all \( t \in [0, T] \), \( w_i(t, \cdot) \in H^2(\mathbb{R} \setminus \{0\}) \) and

\[ \| w_i(t, \cdot) \|_{H^2(\mathbb{R} \setminus \{0\})} \leq M_0, \quad |\sigma^{(w_i)}(t)| \geq \delta_0. \]

Moreover, assume that \( \sigma^{(w_i)} \) is locally Lipschitz on \([0, T]\) and that there exists a function \( K(t) \) such that

\[ |\dot{\sigma}^{(w_i)}(t)| \leq K(t) \quad \text{a.e. } t \in (0, T). \]

Set

\[ z = w_2 - w_1, \quad \sigma^{(z)} = \sigma^{(w_2)} - \sigma^{(w_1)}, \quad M_1(t) = \|z(t, \cdot)\|_{H^1(\mathbb{R} \setminus \{0\})}, \]

\[ M_2(t) = \|z(t, \cdot)\|_{H^2(\mathbb{R} \setminus \{0\})}. \]

Then there exists a constant \( C_2 > 0 \), depending on \( M_0, \delta_0, c_1, \) and \( c_2 \) such that, for every \( x \in [-\frac{1}{2\delta}, \frac{1}{2\delta}] \) and a.e. \( t \in [0, T] \), one has

\[ |F(t, x, w_2) - F(t, x, w_1)| \leq C_2 \cdot \left[ |\dot{\sigma}^{(z)}(t)| \cdot |x| + M_1(t) \cdot (|\ln t| + K(t)) \right]. \]

(3.18)

Moreover, for every \( \delta > 0 \) sufficiently small, it holds

\[ \begin{align*}
& \left\| H \left[ \varphi^{(w_2)}(t, \cdot) - \varphi^{(w_1)}(t, \cdot) \right] \right\|_{H^1(\mathbb{R} \setminus [-\delta, \delta])} + \left\| B^{(w_2)} - B^{(w_1)} \right\|_{H^1(\mathbb{R} \setminus [-\delta, \delta])} \leq C_2 \cdot \frac{M_1(t)}{\delta^{1/2}}, \\
& \left\| F(t, \cdot, w_2) - F(t, \cdot, w_1) \right\|_{H^2(\mathbb{R} \setminus [-\delta, \delta])} \leq C_2 \cdot \left( M_2(t) \cdot (|\ln t| + \frac{1 + K(t)}{\delta^{2/3}}) + \frac{|\dot{\sigma}^{(z)}(t)|}{\delta^{1/2}} \right).
\end{align*} \]

(3.19)

**Proof.**

1. For notational convenience, we set

\[ A^{(z)} = A^{(w_2)} - A^{(w_1)}, \quad B^{(z)} = B^{(w_2)} - B^{(w_1)}, \quad C^{(z)} = C^{(w_2)} - C^{(w_1)}. \]

From [5, Section 3], for every \((t, x) \in [0, T] \times [-\frac{1}{2\delta}, \frac{1}{2\delta}]\), it holds
\[
\begin{align*}
\text{For every } -\frac{1}{2\varepsilon} < x < 0, \text{ by a similar argument, we obtain the same bounds as in (3.21)–(3.23). Therefore}
\end{align*}
\]
\[
\begin{align*}
\|C^{(\varepsilon)}(t, \cdot)\|_{H^1(\mathbb{R} \setminus \{0\})} &\leq O(1) \cdot \left( M_1(t) \cdot \left( |\ln t| + \frac{M_0 + 1}{\delta_0} + K \right) + \left| \hat{\sigma}^{(\varepsilon)}(t) \right| \right), \\
\|C^{(\varepsilon)}(t, \cdot)\|_{H^1(\mathbb{R} \setminus [-\delta, \delta])} &\leq O(1) \cdot \left( M_2(t) \cdot \left( |\ln t| + \frac{M_0 + 1}{\delta_0} + K \right) \cdot \frac{1}{\sqrt{\delta}} + \left| \hat{\sigma}^{(\varepsilon)}(t) \right| \right).
\end{align*}
\]

3. To achieve bound on \( A^{(\varepsilon)} \), for \( 0 < x < \frac{1}{2\varepsilon} \) we compute
\[
\begin{align*}
\left| \varphi^{(w_2)} \varphi_x^{(w_2)} - \varphi^{(w_1)} \varphi_x^{(w_1)} \right| &\leq O(1) \cdot \frac{\left| \hat{\sigma}^{(\varepsilon)}(t) \right|}{\delta_0} \cdot |x \ln |x|| \leq O(1) \cdot \frac{M_1(t)}{\delta_0} \cdot |x \ln |x||, \\
\left| \left( \varphi^{(w_2)} \varphi_x^{(w_2)} - \varphi^{(w_1)} \varphi_x^{(w_1)} \right)_x \right| &\leq O(1) \cdot \frac{\left| \hat{\sigma}^{(\varepsilon)}(t) \right|}{\delta_0} \cdot |\ln |x|| \leq O(1) \cdot \frac{M_1(t)}{\delta_0} \cdot |\ln |x||, \\
\left| \left( \varphi^{(w_2)} \varphi_x^{(w_2)} - \varphi^{(w_1)} \varphi_x^{(w_1)} \right)_{xx} \right| &\leq O(1) \cdot \frac{\left| \hat{\sigma}^{(\varepsilon)}(t) \right|}{\delta_0} \cdot \left| \ln |x| \right| \leq O(1) \cdot \frac{M_1(t)}{\delta_0} \cdot \left| \ln |x| \right|.
\end{align*}
\]
This yields
\[
\begin{align*}
\| \phi^{(\text{w}_2)} \phi^{(\text{w}_2)} - \phi^{(\text{w}_1)} \phi^{(\text{w}_1)} \|_{H^1(\mathbb{R}\setminus\{0\})} & \leq O(1) \cdot \frac{M_1(t)}{\delta_0}, \\
\| \phi^{(\text{w}_2)} \phi^{(\text{w}_2)} - \phi^{(\text{w}_1)} \phi^{(\text{w}_1)} \|_{H^2(\mathbb{R}\setminus[-\delta, \delta])} & \leq O(1) \cdot \frac{M_1(t)}{\delta_0} \cdot \delta^{-2/3}.
\end{align*}
\]

On the other hand, for \(0 < x < \frac{1}{2\varepsilon}\) we observe that
\[
\begin{align*}
\phi^{(\text{w}_2)}(t, x) - \phi^{(\text{w}_1)}(t, x) = (c_2 - 1) \cdot \left[ \phi \left( x, \frac{\sigma^{(\text{w}_2)}(t)}{2} \right) - \phi \left( x, \frac{\sigma^{(\text{w}_1)}(t)}{2} \right) \right] \\
= \frac{c_2 - 1}{2} \cdot \left( \int_0^1 \phi_b \left( x, \frac{\sigma^{(\text{w}_1)}(t)}{2} + \tau \cdot \frac{\sigma^{(\text{w})}(t)}{2} \right) d\tau \right) \cdot \sigma^{(\text{w})}(t) t,
\end{align*}
\]
with \(b_{\tau} = \frac{\sigma^{(\text{w})}(t)}{2} + \tau \cdot \frac{\sigma^{(\text{w})}(t)}{2}\). Thus, by Remark 3.1 it follows
\[
\begin{align*}
\begin{cases}
|H[\phi^{(\text{w}_2)}(\cdot, \cdot) - \phi^{(\text{w}_1)}(\cdot, \cdot)](x)| \leq O(1) \cdot \frac{M_1(t)}{\delta_0}, \\
\frac{d}{dx} H[\phi^{(\text{w}_2)}(\cdot, \cdot) - \phi^{(\text{w}_1)}(\cdot, \cdot)](x) \leq O(1) \cdot M_1(t) \cdot \frac{|\ln |x||}{\delta_0},
\end{cases}
\end{align*}
\]
and
\[
\begin{align*}
\begin{cases}
\|H[\phi^{(\text{w}_2)}(\cdot, \cdot) - \phi^{(\text{w}_1)}(\cdot, \cdot)]\|_{H^1(\mathbb{R}\setminus[-\delta, \delta])} \leq O(1) \cdot M_1(t) \cdot \frac{1}{\delta_0}, \\
\|H[\phi^{(\text{w}_2)}(\cdot, \cdot) - \phi^{(\text{w}_1)}(\cdot, \cdot)]\|_{H^2(\mathbb{R}\setminus[-\delta, \delta])} \leq O(1) \cdot \frac{M_1(t)}{\delta_0} \cdot \delta^{-2/3}.
\end{cases}
\end{align*}
\]

Similarly, one gets the same estimate for \(-\frac{1}{2\varepsilon} < x < 0\). Therefore (3.2) yields
\[
\begin{align*}
\begin{cases}
|A^{(\text{w})}(t, x)| \leq O(1) \cdot \frac{M_1(t)}{\delta_0}, \\
|A^{(\text{w})}_x(t, x)| \leq O(1) \cdot M_1(t) \cdot \frac{|\ln |x||}{\delta_0}, \\
\|A^{(\text{w})}(\cdot, \cdot)\|_{H^1(\mathbb{R}\setminus[-\delta, \delta])} \leq O(1) \cdot \frac{M_1(t)}{\delta_0}, \\
\|A^{(\text{w})}_x(t, \cdot)\|_{H^2(\mathbb{R}\setminus[-\delta, \delta])} \leq O(1) \cdot \frac{M_1(t)}{\delta_0} \cdot \delta^{-2/3}.
\end{cases}
\end{align*}
\]

Finally, combining the estimates (3.20)–(3.26), we obtain (3.18)–(3.19).

\[\square\]

4. Proof of Theorem 2.1

In this section we give a proof of Theorem 2.1 by constructing a solution to the Cauchy problem (2.2) with general initial data of the form (2.6)–(2.7), locally in time. This solution will be obtained as limit of a Cauchy sequence of approximate solutions \(w_n(t, x)\), following the steps (i)–(iii) outlined at the end of Section 2.
**Step 1.** Consider any initial profile \( \tilde{w} \in H^2(\mathbb{R} \setminus \{0\}) \). Let \( \delta_0, M_0 > 0 \) be the constants defined by the identities

\[
\tilde{w}(0-) - \tilde{w}(0+) = 6\delta_0, \quad \|\tilde{w}\|_{H^2(\mathbb{R} \setminus \{0\})} = \frac{M_0}{2}.
\]  

(4.1)

Given two constants \( c_1, c_2 \in \mathbb{R} \), the corresponding initial data of the form (2.6)–(2.7) is

\[
u(0, x) = \tilde{w}(x) + \left( c_1 \cdot \chi_{|x| = 0} + c_2 \cdot \chi_{|x| = \infty} \right) \cdot \phi(x, 0).
\]

Moreover, let \( w_n : [0, T] \times \mathbb{R} \to \mathbb{R} \) be a function such that

\[
|w_n(t, 0 \pm) - \tilde{w}(0 \pm)| \leq \delta_0, \quad \|w_n(t, \cdot)\|_{H^2(\mathbb{R} \setminus \{0\})} \leq M_0, \quad t \in [0, T].
\]  

(4.2)

Set \( \sigma_n(t) = w_n(t, 0-) - w_n(t, 0+) \). As in (2.11), the correction term associated to \( w_n \) is denoted by

\[
\varphi_n(t, x) = \phi(x, 0) + \left( (c_1 - 1) \cdot \chi_{|x| = 0} + (c_2 - 1) \cdot \chi_{|x| = \infty} \right) \cdot \phi \left( x, \frac{\sigma_n(t) t}{2} \right).
\]  

(4.3)

In this step, we will establish the existence and uniqueness of solutions to the linear problem (2.19).

We begin by observing that the speed of all characteristics for (2.19) is

\[
a_n(t, x) = a(t, x, w_n) = \varphi(t, x) + w_n(t, x) - \frac{w_n^-(t) + w_n^+(t)}{2},
\]

where \( \varphi_n(t, x) = \varphi(w_n)(t, x) \), the correction term associated to \( w_n \). From (4.3) and (4.2) it follows that \( \varphi_n(t, 0) = 0 \) and

\[
-4\delta_0 \leq a_n(t, 0+) = -\frac{\sigma_n(t)}{2} \leq -2\delta_0, \quad 2\delta_0 \leq a_n(t, 0-) = \frac{\sigma_n(t)}{2} \leq 4\delta_0.
\]

Furthermore, for any given \((t, x) \in [0, T] \times \left[0, \frac{1}{2e}\right]\), we estimate, using (3.5),

\[
|a_n(t, x) - a_n(t, 0+)| \leq 2\left( 2 + |c_2| |x \ln x| \right) \pi \int_0^x |w_n(t, y)| dy \\
\leq \frac{2(2 + |c_2| |x \ln x|)}{\pi} + x^{1/2} \cdot \left( \int_0^x |w_n(t, y)|^2 dy \right)^{1/2} \leq (2 + |c_2| + M_0) \cdot \sqrt{x}.
\]

Similarly, we also have

\[
|a_n(t, x) - a_n(t, 0-)| \leq (2 + |c_1| + M_0) \cdot \sqrt{|x|}, \quad (t, x) \in [0, T] \times \left[ -\frac{1}{2e}, 0 \right].
\]

In particular, setting

\[
\delta_1 = \frac{1}{4} \cdot \left( \frac{\delta_0}{4 + |c_1| + |c_2| + M_0} \right)^2 \leq \frac{1}{16},
\]  

(4.4)

we have
Next, choose
\[
0 < T < \min\left\{ \frac{\delta_1}{10\delta_0}, \frac{1}{2e} \right\},
\]
and denote by \( t \mapsto x(t; t_0, x_0) \) the solution to the Cauchy problem
\[
\dot{x}(t) = a_n(t, x(t)), \quad x(t_0) = x_0.
\] (4.7)

By (4.5) it follows
\[
\delta_0(t_0 - t) \leq |x(t; t_0, x_0) - x_0| \leq 5\delta_0(t_0 - t), \quad |x_0| \leq \delta_1, \quad 0 \leq t \leq t_0 \leq T. \quad (4.8)
\]

The next lemma provides the Lipschitz continuous dependence of the characteristic curves considered at (4.7).

**Lemma 4.1.** Let \( w_n, \varphi_n \) be as in (4.2)–(4.3). Then there exists a constant \( K_1 > 0 \), depending on \( M_0, \delta_0, c_1, \) and \( c_2 \), such that, for any \( x_1, x_2 \in [-\delta_1, 0[ \) or \( x_1, x_2 \in [0, \delta_1] \), one has
\[
|x(t; \tau, x_2) - x(t; \tau, x_1)| \leq K_1 \cdot |x_2 - x_1|, \quad \text{for all} \quad 0 \leq t \leq \tau \leq T. \quad (4.9)
\]

**Proof.** We shall prove (4.9) for \( x_1, x_2 \in [-\delta_1, 0[ \), the other case being entirely similar. For any \(-\delta_1 \leq z_1 < z_2 < 0\), it holds
\[
|a_n(t, z_2) - a_n(t, z_1)| \leq |w_n(t, z_2) - w_n(t, z_1)| + |\varphi_n(t, z_2) - \varphi_n(t, z_1)|
\leq \left[ M_0 + \frac{4 + 2|c_1|}{\pi} \cdot (1 + |\ln |z_2||) \right] \cdot |z_2 - z_1|.
\]

Therefore, from (4.8), it follows
\[
\frac{d}{dt} |x(t; \tau, x_2) - x(t; \tau, x_1)| \leq \left[ M_0 + \frac{4 + 2|c_1|}{\pi} \cdot (1 + |\ln |\delta_0(\tau - t)||) \right] \cdot |x(t; \tau, x_2) - x(t; \tau, x_1)|,
\]
and this yields (4.9). \( \square \)

From (4.5), by the same arguments as in [5, Lemma 4.1], one obtains:

**Lemma 4.2.** Let \( w_n, \varphi_n \) be as in (4.2)–(4.3). There exists \( T > 0 \) sufficiently small, depending only on \( M_0, \delta_0, c_1, c_2 \), such that, for every \( \tau \in [0, T] \) and any solution \( v \) of the linear equation
\[
\nu_t + a_n(t, x) \cdot \nu_x = 0, \quad v(0, \cdot) = \tilde{v} \in H^2(\mathbb{R} \setminus [-\delta_0\tau, \delta_0\tau]),
\]
one has
\[
\|v(\tau, \cdot)\|_{H^2(\mathbb{R} \setminus \{0\})} \leq \frac{3}{2} \cdot \|	ilde{v}\|_{H^2(\mathbb{R} \setminus [-\delta_0\tau, \delta_0\tau])}.
\]

**Step 2.** Consider a sequence of approximate solutions \( w^{(k)} \) to (2.19), inductively defined as follows.
\[ w^{(1)}(t, \cdot) \equiv \bar{w}(\cdot) \] for all \( t \geq 0 \).

- For every \( k \geq 1 \), \( w^{(k+1)}(t, \cdot) \) solves the linear equation

\[ w_t + a_n(t, x) \cdot w_x = F^{(k)}(t, x), \quad w(0, \cdot) = \bar{w}(\cdot) \]

with \( F^{(k)}(t, x) \equiv F(t, x, w^{(k)}) \). Equivalently, \( w^{(k+1)} \) satisfies the integral identities

\[
w^{(k+1)}(t_0, x_0) = \bar{w}(x(0; t_0, x_0)) + \int_0^t F^{(k)}(t, x(t; t_0, x_0)) dt. \tag{4.10}
\]

The following lemma provides a priori estimates on \( w^{(k)} \), uniformly valid for all \( k \geq 1 \).

**Lemma 4.3.** Let \( w_n, \varphi_n \) be as in (4.2)–(4.3). Then there exists \( T > 0 \) sufficiently small, depending only on \( M_0, \delta_0, c_1, c_2 \), and satisfying (4.6) so that the following holds. For every \( k \geq 1 \) and a.e. \( \tau \in [0, T] \), one has

\[
|w^{(k)}(\tau, 0^\pm) - \bar{w}(0^\pm)| \leq \delta_0, \tag{4.11}
\]

\[
|\sigma^{(k)}(\tau)| \leq 4C_1(1 + M_0) \cdot |\ln \tau|, \tag{4.12}
\]

\[
||w^{(k)}(\tau, \cdot)||_{H^2(\mathbb{R}\setminus \{0\})} \leq M_0, \tag{4.13}
\]

for some constant \( C_1 > 0 \).

**Proof.**

1. It is clear that (4.11)–(4.13) hold for \( k = 1 \). By induction, assume that (4.11) holds for a given \( k \geq 1 \). By the assumptions (4.1) and (4.11), for all \( \tau \in [0, T] \) one obtains

\[
\sigma^{(k)}(\tau) \geq \bar{w}(0-) - \bar{w}(0+) - |w^{(k)}(\tau, 0^+) - \bar{w}(0^+)| - |w^{(k)}(\tau, 0-) - \bar{w}(0^-)| \\
\geq 4\delta_0.
\]

For a fixed \( \tau \in [0, T] \), let \( x^\pm : [0, \tau] \mapsto \mathbb{R} \) be the characteristics which reach the origin at time \( \tau \), from the left and the right, respectively. Recalling (4.10), (3.8), (4.1), and (4.8), we estimate

\[
|w^{(k+1)}(\tau, 0^\pm) - \bar{w}(0^\pm)| \leq |\bar{w}(x^+(0)) - \bar{w}(0^\pm)| + \int_0^\tau |F^{(k)}(t, x^+(t))| dt \\
\leq 3M_0\delta_0\tau + C_1 \cdot \int_0^\tau \left(1 + M_0\right) \cdot |\ln t| + \frac{|\sigma^{(k)}(t)|}{|\sigma^{(k)}(t)|} \cdot |x^+(t)| dt \\
\leq 3M_0\delta_0\tau + C_1 \cdot (1 + M_0) \cdot \int_0^\tau (1 + 5C_1(\tau - t)) \cdot |\ln(t)| dt \\
\leq O(1) \cdot (1 + M_0) \cdot |\ln(\tau)| \cdot \tau \leq O(1) \cdot (1 + M_0) \cdot |\ln(T)| \cdot T
\]

and this shows that \( w^{(k+1)} \) satisfies (4.11), provided that \( T > 0 \) is chosen sufficiently small, depending only on \( M_0, \delta_0, c_1, \) and \( c_2 \).

2. For any \( \tau \in [0, T] \) and \( -\delta_1 \leq \bar{x}_2 < \bar{x}_1 < 0 \), consider the characteristics

\[
t \mapsto x_1(t) = x(t; \tau, \bar{x}_1), \quad t \mapsto x_2(t) = x(t; \tau, \bar{x}_2).
\]
Using (4.10), (4.9), (3.8), (4.11), and (4.8), we estimate
\[
|w^{(k+1)}(\tau, \bar{x}_2) - w^{(k+1)}(\tau, \bar{x}_1)| \\
\leq |\bar{w}(x_2(0)) - \bar{w}(x_1(0))| + \int_0^\tau |F^{(k)}(t, x_2(t)) - F^{(k)}(t, x_1(t))|dt \\
\leq M_0K_1 \cdot |\bar{x}_2 - \bar{x}_1| + C_1 \cdot \int_0^\tau \left((1 + M_0) \cdot |x_1(t)|^{-1/4} + \frac{\|\sigma^{(k)}(t)\|}{\|\sigma^{(k)}(t)\|} \cdot |x_2(t) - x_1(t)|dt \\
\leq M_0K_1 \cdot \left(1 + C/(1) \cdot \left(1 + \frac{1}{M_0} \cdot \left[\left(\frac{\tau}{\delta_0}\right)^{1/4} + \frac{\tau \ln \tau}{\delta_0}\right]\right)\right) \cdot |\bar{x}_2 - \bar{x}_1|.
\]

Therefore, choosing \(T > 0\) sufficiently small, we obtain
\[
|w^{(k+1)}(\tau, x)| \leq 3M_0K_1 \quad \text{for all} \quad \tau \in [0, T], x \in [-\delta_1, 0]. \quad (4.14)
\]

An entirely similar estimate holds for \(\tau \in [0, T], x \in [0, \delta_1].\)

3. Next, given any \(0 \leq \tau_1 < \tau_2 \leq T\), denote by \(t \mapsto x^+_{\tau_1}(t) = x(t; \tau, 0, \pm)\) the characteristic which reaches the origin at time \(\tau_2\) from the positive or negative side, respectively. Recalling (4.9)–(4.11), (3.8), and (4.14), we estimate
\[
|w^{(k+1)}(\tau_2, 0) - w^{(k+1)}(\tau_1, 0)| \\
\leq |w^{(k+1)}(\tau_2, x^+_{\tau_1}(\tau_1)) - w^{(k+1)}(\tau_1, 0)| + \int_{\tau_1}^{\tau_2} |F^{(k)}(t, x^+_{\tau_1}(t))|dt \\
\leq 3M_0K_1|x^+_{\tau_1}(\tau_1)| + C_1 \cdot \int_{\tau_1}^{\tau_2} \left((1 + M_0) \cdot |\ln t| + \frac{\|\sigma^{(k)}(t)\|}{\|\sigma^{(k)}(t)\|} \cdot |x^+_{\tau_1}(t)|\right)dt \\
\leq 15M_0K_1\delta_0(\tau_2 - \tau_1) + C_1(1 + M_0) \int_{\tau_1}^{\tau_2} |\ln t|(1 + 5C_1(\tau_2 - t))dt \\
\leq (15M_0K_1\delta_0 + C_1(1 + M_0)|\ln(\tau_1)| \cdot (\tau_2 - \tau_1) \leq 2C_1(1 + M_0)|\ln(\tau_1)| \cdot (\tau_2 - \tau_1),
\]

provided that \(T > 0\) is sufficiently small. In particular, we have
\[
|\sigma^{(k+1)}(\tau_2) - \sigma^{(k+1)}(\tau_1)| \leq 4C_1(1 + M_0)|\ln(\tau_1)| \cdot (\tau_2 - \tau_1).
\]

This shows that \(\sigma^{(k+1)}\) satisfies (4.12).

4. Finally, from Lemma 4.2, Lemma 3.2, (4.12), and Duhamel’s formula, for all \(\tau \in [0, T]\) we obtain
\[
\|w^{(k+1)}(\tau, \cdot)\|_{H^2(\mathbb{R}\setminus\{0\})} \\
\leq \frac{3}{2} \cdot \|\bar{w}\|_{H^2(\mathbb{R}\setminus[-\delta_0, \delta_0])} + \frac{3}{2} \cdot \int_0^\tau \|F^{(k)}(t, \cdot)\|_{H^2(\mathbb{R}\setminus[-\delta_0(\tau-t), \delta_0(\tau-t)])}dt \\
\leq \frac{3M_0}{4} + \frac{3}{2} \cdot C_1(1 + M_0) \int_0^\tau \left(1 + \frac{C_1}{\delta_0} \cdot |\ln t|\right) \cdot \delta_0^{-2/3} \cdot (\tau - t)^{-2/3} + |\ln t|dt \\
\leq \frac{3M_0}{4} + \frac{3}{2} \cdot C_1(1 + M_0) \cdot \left[6\left(1 + \frac{C_1}{\delta_0} \cdot |\ln t|\right)\delta_0^{-2/3} \tau^{1/3} + |\ln t|\right] \leq M_0,
\]
provided that $T > 0$ is sufficiently small, depending only on $M_0, \delta_0, c_1$, and $c_2$. This shows that (4.13) is satisfied by $w^{(k+1)}$ as well.

Thanks to the above estimates, we can now prove that the sequence of approximations $w^{(k)}$ is Cauchy and converges to a solution $w$ of the linear problem (2.19). This is a key step toward the proof of Theorem 2.1.

**Lemma 4.4.** Let $w_n$, $\varphi_n$ be as in (4.2)–(4.3). Then, for some $T > 0$ sufficiently small, depending only on $M_0, \delta_0, c_1, c_2$, the sequence of approximations $(w^{(k)})_{k \geq 1}$ converges to a limit function $w$ in $L^\infty([0, T]; H^2(\mathbb{R} \setminus \{0\}))$, i.e.,

$$\lim_{k \to \infty} \sup_{t \in [0, T]} \|w^{(k)}(t, \cdot) - w(t, \cdot)\|_{H^2(\mathbb{R} \setminus \{0\})} = 0.$$ 

The function $w$ provides a solution to the Cauchy problem (2.19) and satisfies

$|w(\tau, 0 \pm) - \tilde{w}(0 \pm)| \leq \delta_0, \quad \|w(t, \cdot)\|_{H^2(\mathbb{R} \setminus \{0\})} \leq M_0, \quad t \in [0, T]$ \hspace{1cm} (4.15)

Moreover, $\sigma(t) \doteq w(t, 0-) - w(t, 0+)$ is locally Lipschitz in $(0, T)$ and

$$|\dot{\sigma}(t)| \leq 4C_1(1 + M_0) \cdot |\ln t|, \quad a.e. \ t \in (0, T).$$ \hspace{1cm} (4.16)

**Proof.**

1. For any $k \geq 1$, we set

$$\begin{cases}
    z^{(k)}(t) = w^{(k+1)} - w^{(k)}, \\
    \sigma_z^{(k)}(t) = z^{(k)}(t, 0-) - z^{(k)}(t, 0+), \\
    M_z^{(k)}(t) = \|z^{(k)}(t, \cdot)\|_{H^2(\mathbb{R} \setminus \{0\})}, \\
    \beta_k(t) = \sup_{t \in [0, t]} M_z^{(k)}(t), \quad \alpha_k(t) = \sup_{t \in [0, t]} |\dot{\sigma}_z^{(k)}(t)|.
\end{cases}$$

(4.17)

Recalling Lemma 3.3, Lemma 4.2, and Lemma 4.3, and using Duhamel’s formula, we estimate

$$M_z^{(k+1)}(\tau) \leq \frac{3}{2} \int_{0}^{\tau} \|F^{(k+1)}(t, \cdot) - F^{(k)}(t, \cdot)\|_{H^2(\mathbb{R} \setminus [-\delta_0(\tau-t), \delta_0(\tau-t)])} dt$$

$$\leq C_3 \cdot \int_{0}^{\tau} \beta_k(t) \cdot |\ln t| \left(1 + \frac{1}{(\tau-t)^{2/3}}\right) + \frac{\alpha_k(t)}{\sqrt{\tau-t}} dt$$

$$\leq C_4 \cdot \left(\beta_k(\tau)\tau^{1/3} + \alpha_k(\tau)\tau^{1/2}\right),$$

and this implies

$$\beta_{k+1}(\tau) \leq C_4 \cdot \left(\beta_k(\tau)\tau^{1/3} + \alpha_k(\tau)\tau^{1/2}\right), \quad \tau \in [0, T], \ k \geq 1,$$ \hspace{1cm} (4.18)

for some constant $C_3, C_4 > 0$ depending only on $M_0, \delta_0, c_1, c_2$.

2. We now establish a bound on $\|\dot{\sigma}^{(k+1)}\|_{L^\infty([0, T])}$. Given any $0 < \tau_1 < \tau_2 \leq T$, denote by $t \mapsto x^{(\tau)}(t) \doteq x(t; \tau, 0 \pm)$ the characteristics, which reach the origin at time $\tau_0$ from the positive or negative side, respectively. Using (3.18), (4.12), and (4.8) we obtain...
\[ |z^{(k+1)}(\tau, 0) - z^{(k+1)}(\tau_1, 0_+)| \]
\[ \leq |z^{(k+1)}(\tau_1, x_2^+ (\tau_1)) - z^{(k+1)}(\tau_1, 0)| + \int_{\tau_1}^{\tau_2} \left| F^{(k+1)}(t, x_2^+ (t)) - F^{(k)}(t, x_2^+ (t)) \right| dt \]
\[ \leq \beta_{k+1} \cdot |x_2^+ (\tau_1)| + C_5 \cdot \int_{\tau_1}^{\tau_2} x_2^+ (t) \cdot |x_2^+ (t)| + \beta_k (t) \cdot |\ln t| \cdot dt \]
\[ \leq (5\beta_{k+1} (\tau_2) \delta_0 + C_6 \cdot [\beta_k (\tau_2) \cdot |\ln \tau_1| + x_k (\tau_2) (\tau_2 - \tau_1)] \cdot (\tau_2 - \tau_1), \]

for some constants \(C_5 > 0\) and \(C_6 > 0\) depending only on \(M_0, \delta_0, c_1,\) and \(c_2.\) Thus, for \(0 < T < \delta_0\) sufficiently small, we obtain
\[ x_{k+1} (\tau) \leq 10\beta_{k+1} (\tau) \delta_0 + 2C_5 \beta_k (\tau) |\ln \tau| \quad \tau \in [0, T], k \geq 1, \quad (4.19) \]
and (4.18) yields
\[ \beta_{k+1} (\tau) \leq C_7 \cdot (\beta_k (\tau) + \beta_{k-1} (\tau)) \cdot \tau^{1/3}. \]

for some \(C_7 > 0\) depending only on \(M_0, \delta_0, c_1,\) and \(c_2.\) In particular, for \(T > 0\) sufficiently small, one has
\[ \beta_{k+1} (\tau) + \frac{1}{2} \beta_k (\tau) \leq \frac{3}{4} \cdot \left( \beta_k (\tau) + \frac{1}{2} \beta_{k-1} (\tau) \right), \]
which implies
\[ \sum_{k=1}^{\infty} \sup_{\tau \in (0, T]} \|z^{(k)}(\tau, \cdot)\|_{H^2(\mathbb{R} \setminus \{0\})} < \infty. \]

We thus conclude that \((w^{(k)})_{k \geq 1}\) is a Cauchy sequence in \(L^\infty([0, T], H^2(\mathbb{R} \setminus \{0\}))\) and converges to a limit function \(w \in L^\infty([0, T], H^2(\mathbb{R} \setminus \{0\}))\), which provides the solution to the linear problem (2.19), and satisfies (4.15). Moreover, since \(\lim_{k \to -\infty} w^{(k)} (\tau, 0_0) = w(\tau, 0_0),\) one has that \(\lim_{k \to -\infty} \sigma^{(k)} (\tau) = \sigma (\tau)\) for all \(\tau \in [0, T].\) Thus, from (4.12), \(\sigma (\cdot)\) is locally Lipschitz in \((0, T)\) and satisfies (4.16).

We are now ready to complete the proof of our first main result.

**Proof of Theorem 2.1.** As outlined at the end of Section 2, we construct, by induction, a sequence of approximate solutions \((w_n)_{n \geq 1}\) where each \(w_n\) is the solution to the linear problem (2.19). For some \(T > 0\) small enough, depending only on \(M_0, \delta_0, c_1,\) and \(c_2,\) we claim that
\[ \sum_{n \geq 2} \|w_n (\tau) - w_{n-1} (\tau)\|_{H^2(\mathbb{R} \setminus \{0\})} < \infty \quad \text{for all } \tau \in [0, T]. \quad (4.20) \]

For a fixed \(n \geq 2,\) we define
\[ W_n \overset{\Delta}{=} w_n - w_{n-1}, \quad a_n (t, x) \overset{\Delta}{=} a(t, x, w_n), \quad A_n (t, x) \overset{\Delta}{=} a_n (t, x) - a_{n-1} (t, x), \]
\[ v_n \overset{\Delta}{=} \varphi (w_n) - \varphi (\cdot, 0), \quad V_n \overset{\Delta}{=} v_n - v_{n-1}, \quad \beta_n (t) \overset{\Delta}{=} \sup_{s \in [0, t]} \|W_n\|_{H^2(\mathbb{R} \setminus \{0\})}. \]

Set \(Z_n = W_n + V_n.\) From the above definitions, by (2.19) it follows
with
\[ G_{n+1} = B^{\varphi_{n+1}} - B^{\varphi_n} + H[\varphi^{\varphi_{n+1}} - \varphi^{\varphi_n}] - (\varphi^{\varphi_{n+1}} - \varphi^{\varphi_n}) \cdot \varphi_x(t, 0). \]

Recalling the first inequality in (3.19) and (4.15), we estimate
\[
\begin{aligned}
\| A_n(t, \cdot) \cdot w_n(t, \cdot) \|_{H^1(\mathbb{R}\setminus[-\delta, \delta])} &\leq C_7 \cdot M_n(t) \leq C_7 \cdot \beta_n(t), \\
\| A_{n+1}(t, \cdot) \cdot v_{n+1}(t, \cdot) \|_{H^1(\mathbb{R}\setminus[-\delta, \delta])} &\leq C_7 \cdot \frac{M_{n+1}(t)}{\delta^{1/2}} \leq C_7 \cdot \frac{\beta_{n+1}(t)}{\delta^{1/2}}, \\
\| G_{n+1}(t, \cdot) \|_{H^1(\mathbb{R}\setminus[-\delta, \delta])} &\leq C_7 \cdot \frac{M_{n+1}(t)}{\delta^{1/2}} \leq C_7 \cdot \frac{\beta_{n+1}(t)}{\delta^{1/2}}.
\end{aligned}
\]

for some constant \( C_7 > 0 \) depending only on \( M_0, \delta_0, c_1, \) and \( c_2 \). Hence, choosing \( T > 0 \) sufficiently small, we have, using Duhamel’s formula,
\[
\begin{aligned}
\| Z_{n+1}(\tau, \cdot) \|_{H^1(\mathbb{R}\setminus\{0\})} &\leq \frac{3}{2} \int_0^\tau \| G_{n+1} - A_n w_{n,x} - A_{n+1} v_{n+1,x} \|_{H^1(\mathbb{R}\setminus[-\delta_0(\tau-t), \delta_0(\tau-t)])} \, dt \\
&\leq \frac{3C_8}{2} \int_0^\tau \beta_n(t) + \frac{\beta_{n+1}(t)}{(\tau-t)^{1/2}} \, dt = \frac{3C_8}{2} \left( \beta_n(\tau) \cdot \tau + 2\beta_{n+1}(\tau) \tau^{1/2} \right)
\end{aligned}
\]

for some constant \( C_8 > 0 \). On the other hand, (2.11), (4.21), and (3.25) imply
\[
\| V_{n+1}(\tau, \cdot) \|_{H^1(\mathbb{R}\setminus\{0\})} \leq C_9 \cdot \| W_{n+1}(\tau, \cdot) \|_{H^1(\mathbb{R}\setminus\{0\})} \cdot \tau^{1/4},
\]

and (4.23) yields
\[
\| W_{n+1}(\tau, \cdot) \|_{H^1(\mathbb{R}\setminus\{0\})} \leq \frac{3C_8}{2} \left( \beta_n(\tau) \cdot \tau + 2\beta_{n+1}(\tau) \tau^{1/2} \right) + C_9 \cdot \| W_{n+1}(\tau, \cdot) \|_{H^1(\mathbb{R}\setminus\{0\})} \cdot \tau^{1/4}.
\]

for some constant \( C_9 > 0 \) depending only on \( M_0, \delta_0, c_1, \) and \( c_2 \). In particular, for \( T > 0 \) sufficiently small, one has that
\[
\beta_{n+1}(\tau) \leq \frac{1}{2} \cdot \beta_n(\tau) \quad \text{for all } \tau \in [0, T].
\]

Thus, (4.20) holds and for every \( t \in [0, T] \) the sequence of approximations \( w_{n}(t, \cdot) \) is Cauchy in the space \( H^1(\mathbb{R}\setminus\{0\}) \), and hence it converges to a unique limit \( w(t, \cdot) \).

It remains to check that this limit function \( w \) is an entropic solution, i.e., it satisfies, cf. (2.2), (2.8), and (2.6),
\[
(w + \varphi^{\varphi(w)})(t_0, x_0) = (\tilde{w} + \varphi)(x(0; t_0, x_0)) + \int_0^{t_0} H[w + \varphi^{\varphi(w)}](t, x(t; t_0, x_0)) \, dt,
\]

where \( t \mapsto x(t; t_0, x_0) \) is the characteristics curve, obtained by solving (2.16). This follows from slightly rewriting (2.19), which yields
\[
(w_{n+1} + \varphi^{(w_{n+1})})(t_0, x_0) = (\dot{w} + \varphi)(x_n(0; t_0, x_0)) + \int_0^{t_0} H \left[ w_{n+1} + \varphi^{(w_{n+1})} \right](t, x_n(t; t_0, x_0)) \, dt
- \int_0^{t_0} \left( Z_{n+1} - \frac{W_{n+1}^-(t) + W_{n+1}^+(t)}{2} \right) \varphi^{(w_{n+1})}(t, x_n(t; t_0, x_0)) \, dt,
\]
where \( t \mapsto x_n(t; t_0, x_0) \) denotes the characteristic curve, obtained by solving (4.7)

Finally, to prove uniqueness, assume that \( \hat{w}, w \) are two entropic solutions. We then define
\[
W \doteq \hat{w} - w, \quad \beta(\tau) \doteq \sup_{s \in [0, \tau]} \| W(s, \cdot) \|_{H^1(\mathbb{R} \setminus \{0\})}.
\]

The arguments used in the previous steps now yield the inequality
\[
\beta(\tau) \leq \frac{1}{2} \beta(\tau) \quad \text{for all } \tau \in [0, T],
\]
which implies \( \beta(\tau) = 0 \) for all \( \tau \in [0, T] \) and completes the proof.

\section{Two interacting shocks}

In this section, denote by \( u(t, x) \) the solution to Burgers’ equation
\[
u_t + u_n = 0, \quad u(0, x) = \bar{u}(x),
\]
and by \( v(t, x) \) the solution to the perturbed linearized equation
\[
v_t + uv_x = H[u(t, \cdot)](x), \quad v(0, x) = \bar{v}(x).
\]

By the method of characteristics, at all points where \( u \) is continuous, one has
\[
v(\tau, y) = \bar{v}(y - \tau u(\tau, y)) + \int_0^\tau H[u(t, \cdot)](y - (\tau - t) u(\tau, y)) \, dt.
\]

We expect that \( v \) can provide a leading order correction term, in an ansatz describing the solution with two interacting shocks to the Burgers-Hilbert equation (1.1).

To fix the ideas, consider a piecewise constant solution to Burgers’ equation containing two interacting shocks with initial data
\[
\begin{cases}
u(0, x) = \bar{u}(x) = \begin{cases}
u^\ell & \text{if } x < \bar{x}_1, \\
u^m & \text{if } \bar{x}_1 < x < \bar{x}_2, \\
u^r & \text{if } \bar{x}_2 < x.
\end{cases}
\end{cases}
\]

with \( \nu^\ell > \nu^m > \nu^r \). Setting
\[
\begin{align*}
\sigma_1 &= \nu^\ell - \nu^m, \\
\sigma_2 &= \nu^m - \nu^r, \\
a_1 &= \frac{\nu^\ell + \nu^m}{2}, \\
a_2 &= \frac{\nu^m + \nu^r}{2}, \\
x_1(t) &= \bar{x}_1 + a_1 t, \\
x_2(t) &= \bar{x}_2 + a_2 t,
\end{align*}
\]
we thus have
Case 1: \( y < x_1(t) \). We then have

\[
I(\tau, y) \approx \frac{2}{\pi} \left[ (x_1(\tau) - y) \ln (x_1(\tau) - y) + \frac{\sigma_2}{2\sigma_1 + \sigma_2} (x_2(\tau) - y) \ln (x_2(\tau) - y) \right].
\]

(5.8)

Case 2: \( x_1(\tau) < y < x_2(\tau) \). We then have

\[
I(\tau, y) \approx \frac{2}{\pi} \left[ (y - x_1(\tau)) \ln (y - x_1(\tau)) + (x_2(\tau) - y) \ln (x_2(\tau) - y) \right].
\]

(5.9)

Case 3: \( x_2(\tau) < y \). We then have

\[
I(\tau, y) \approx \frac{2}{\pi} \left[ \frac{\sigma_1}{\sigma_1 + 2\sigma_2} (y - x_1(\tau)) \ln (y - x_1(\tau)) + (y - x_2(\tau)) \ln (y - x_2(\tau)) \right].
\]

(5.10)

Next, consider a more general piecewise smooth solution \( u \) of the Burgers–Hilbert equation (1.1) with two interacting shocks located at points \( x_1(\tau) < x_2(\tau) \) with strengths

\[
\begin{align*}
\sigma_1(\tau) &= u(\tau, x_1(\tau)-) - u(\tau, x_1(\tau)+), \\
\sigma_2(\tau) &= u(\tau, x_2(\tau)-) - u(\tau, x_2(\tau)+),
\end{align*}
\]

(5.11)

respectively. As the interaction time \( T \) is approached, we expect that the two limits will coincide

\[
\lim_{\tau \to T^-} u(\tau, x_1(\tau)+) = \lim_{\tau \to T^-} u(\tau, x_2(\tau)-).
\]

Furthermore, as shown in Figure 2, all characteristics located in the triangular region between the two shocks will hit one of them within time \( T \).
To construct such solutions, we should thus try with an ansatz of the form

\[ u(s, y) = w(s, y) + /y(s, y), \]  

where

\[ w(s, \cdot) \in H^2([-\infty, x_1(s)] \cup [x_1(s), x_2(s)] \cup [x_2(s), +\infty]). \]

Moreover, in view of (5.8)–(5.10), the correction \( / \) should be defined as

\[
\phi(s, y) = \begin{cases} 
2 \pi \left[ (x_1(s) - y) \ln (x_1(s) - y) + \frac{\sigma_1(s)}{2\sigma_1(s) + \sigma_2(s)} (x_2(s) - y) \ln (x_2(s) - y) \right] & \text{if } y < x_1(s), \\
2 \pi \left[ (y - x_1(s)) \ln (y - x_1(s)) + (x_2(s) - y) \ln (x_2(s) - y) \right] & \text{if } x_1(s) < y < x_2(s), \\
2 \pi \left[ \frac{\sigma_1(s)}{\sigma_1(s) + 2\sigma_2(s)} (y - x_1(s)) \ln (y - x_1(s)) + (y - x_2(s)) \ln (y - x_2(s)) \right] & \text{if } x_2(s) < y.
\end{cases}
\]

Note that, for each fixed time \( s < T \), since \( x_1(s) < x_2(s) \), for \( y < x_1(s) \), the term \( \ln (x_2(s) - y) \) remains smooth. The same is true for the term \( \ln (y - x_1(s)) \) in the region where \( y > x_2(s) \). As a consequence, the asymptotic profile of the function \( \phi(s, \cdot) \) near both points \( x_1(s) \) and \( x_2(s) \) has the same “\( x \ln |x| \)” singularity that we encountered before. However, these two additional terms cannot be removed from the definition of \( \phi \), because they are not uniformly smooth as \( s \to T - \).

6. Constructing a solution with two interacting shocks

We consider here a solution of the Burgers-Hilbert equation (1.1), which is piecewise continuous and which has two shocks located at the points \( y_1(t) < y_2(t) \). By the Rankine-Hugoniot conditions, the time derivatives satisfy

\[ \dot{y}_i(t) = \frac{u_i^-(t) + u_i^+(t)}{2}, \quad i = 1, 2. \]

Here \( u_i^\pm(t) = u_i(t, y_i(t) \pm) \) denote the left and the right limits of \( u(t, x) \) as \( x \to y_i(t) \). Throughout the following, we assume that

![Figure 2. The characteristics for a solution to Burgers’ equation with two shocks at \( x_1(t) < x_2(t) \).](image-url)
\[
\frac{u_1(t) + u_1^+ (t)}{2} = y_1'(t) \quad \Rightarrow \quad y_2'(t) = \frac{u_2^- (t) + u_2^+ (t)}{2}.
\]

The function \( \tau = y_1 - y_2 \) is negative and monotone increasing. It will be useful to change the space and the time variables, so that in the new variables \( \tilde{t}, \tilde{x} \) the location of one shock is fixed, while the other moves with constant speed 1. For this purpose, we set

\[
\tilde{x} = x - y_2(t), \quad \tilde{t} = \tau(t) < 0.
\]

As a consequence, the two shocks, in the new coordinate system, are located at \( y_1(\tilde{t}) = \tilde{t}, \quad y_2(\tilde{t}) = 0 \), and interact at the point \((\tilde{t}, \tilde{x}) = (0,0)\). Introducing the function

\[
v(\tau(t), x) = u(t, x + y_2(t)), \tag{6.2}
\]

we define the left and right values

\[
v_1^+(\tau(t)) = v(\tau(t), \tau(t)^+) = u(t, y_1(t)^+) , \quad v_2^+(\tau(t)) = v(\tau(t), 0^+) = u(t, y_2(t)^+). \tag{6.3}
\]

The change of variables (6.2) yields

\[
v_\tau(\tau, x) = u_\tau(t, x + y_2(t)), \quad v_\tau(\tau, x) = \frac{u_1(t, x + y_2(t)) + \dot{y}_2(t) \cdot u_x(t, x + y_2(t))}{\dot{y}_1(t) - \dot{y}_2(t)}.
\]

Therefore, (1.1) implies

\[
v_\tau(\tau(t), x) + \left[ v(\tau(t), x) - \dot{y}_2(t) \right] \cdot v_\tau(\tau(t), x) = \frac{H[v(\tau(t), \cdot)](x)}{\dot{y}_1(t) - \dot{y}_2(t)}. \tag{6.4}
\]

Thus, by (6.1), (6.3), and (6.4), we can recast the original (1.1) in the following equivalent form

\[
u_t + \frac{1}{a_1(t) - a_2(t)} \cdot [u - a_2(t)] \cdot u_x = \frac{H[u]}{a_1(t) - a_2(t)}. \tag{6.5}
\]

Given \( \tau_0 < 0 \), for \( t \in [\tau_0, 0] \) the two functions

\[
a_1(t) = \frac{u_1^- (t) + u_1^+ (t)}{2}, \quad a_2(t) = \frac{u_2^- (t) + u_2^+ (t)}{2}, \tag{6.6}
\]

yield the speeds of the two shocks in the original coordinates, as shown in Figure 3.

We shall construct the solution of (6.5) in the form

\[
u(t, x) = w(t, x) + \varphi(t, x) \quad \text{for all } (t, x) \in [\tau_0, 0] \times \mathbb{R}. \tag{6.7}
\]

Here \( \varphi \) is a continuous function, which satisfies \( \varphi(t, t) = \varphi(t, 0) = 0 \), while

\[
w(t, \cdot) \in H^2([-\infty, t[ \cup ]t, 0[ \cup ]0, +\infty[) \quad \text{for all } t \in [\tau_0, 0]. \tag{6.8}
\]

According to (6.8), the function \( w(t, \cdot) \) is continuously differentiable outside the two points \( x = t \) and \( x = 0 \). Moreover, the distributional derivative \( D_x w(t, \cdot) \) is an \( L^2 \) function restricted to each interval \( ]-\infty, t[ \cup ]t, 0[ \cup ]0, +\infty[ \). However, both \( w(t, \cdot) \) and \( w_x(t, \cdot) \) can have a jump at \( x = t \) and at \( x = 0 \). At the points \( (t, t) \) and \( (t, 0) \), the
following traces are well defined:

\[
\begin{align*}
    w^-_1 (t) & \doteq w(t, t-), & b^-_1 (t) & \doteq w_x(t, t-), \\
    w^+_1 (t) & \doteq w(t, t+), & b^+_1 (t) & \doteq w_x(t, t+), \\
    w^-_2 (t) & \doteq w(t, 0-), & b^-_2 (t) & \doteq w_x(t, 0-), \\
    w^+_2 (t) & \doteq w(t, 0+), & b^+_2 (t) & \doteq w_x(t, 0+).
\end{align*}
\]

(6.9)

For the shocks to be entropy admissible, the inequalities

\[
    w^-_1 (t) > w^+_1 (t), \quad w^-_2 (t) > w^+_2 (t),
\]

will always be assumed. Writing

\[
    a^{(w)}_1 (t) \doteq \frac{w^-_1 (t) + w^+_1 (t)}{2}, \quad a^{(w)}_2 (t) \doteq \frac{w^-_2 (t) + w^+_2 (t)}{2} ,
\]

(6.12)

(6.5) reads

\[
    w_t + a(t, x, w) \cdot w_x = F(t, x, w),
\]

(6.13)

where \( a \) and \( F \) are given by

\[
    a(t, x, w) = \frac{w(t, x) + \varphi^{(w)}(t, x) - a^{(w)}_2(t)}{a^{(w)}_1(t) - a^{(w)}_2(t)},
\]

(6.14)

\[
    F(t, x, w) = \left[ \frac{H[w] - (w - a^{(w)}_2(t)) \cdot \varphi^{(w)}_x}{a^{(w)}_1(t) - a^{(w)}_2(t)} - \varphi^{(w)}_t \right] + \frac{H[\varphi^{(w)}] - \varphi^{(w)} \varphi^{(w)}_x}{a^{(w)}_1(t) - a^{(w)}_2(t)},
\]

(6.15)

respectively. Here the function \( \varphi^{(w)}(t, x) \) is chosen in such a way that a cancelation between leading order terms near to the location of the two shocks at \( x = t \) and at \( x = 0 \) is achieved. More precisely, in view of (5.14) and recalling (2.3) and (2.4), we set

\[
    \varphi_0 (x) = \varphi(x, 0) = \frac{2\eta(x)}{\pi} \cdot |x| \ln |x|,
\]

(6.16)

and define
\[
\varphi^{(w)}(t, x) = \begin{cases} 
\phi_0(x - t) + \frac{\sigma_2^{(w)}(t)}{2\sigma_1^{(w)}(t) + \sigma_2^{(w)}(t)} \cdot (\phi_0(x) - \phi_0(t)) & \text{if } x < t, \\
\phi_0(x - t) + \phi_0(x) - \phi_0(t) & \text{if } t < x < 0, \\
\frac{\sigma_1^{(w)}(t)}{\sigma_1^{(w)}(t) + \sigma_2^{(w)}(t)} \cdot (\phi_0(x - t) - \phi_0(t)) + \phi_0(x) & \text{if } 0 < x.
\end{cases}
\]

The following theorem provides the existence of solutions to the Cauchy problem for (1.1) where the initial datum contains two shocks. In particular, the solution to (6.5) is constructed up to the time where the two shocks interact. Furthermore, the solution is of the form (6.7), where \( \varphi = \varphi^{(w)} \), the corrector function defined in (6.17).

**Theorem 6.1.** For any given constants \( b, M_0, \delta_1, \delta_2 > 0 \), there exists \( \varepsilon_0 > 0 \) small enough and a constant \( K \) such that the following holds.

Consider any \( \tau_0 \in [0, \varepsilon_0] \) and any initial condition \( \tilde{w} \in H^2(\mathbb{R}\setminus\{\tau_0, 0\}) \) such that

\[
\begin{aligned}
\|\tilde{w}\|_{H^2(\mathbb{R}\setminus\{\tau_0, 0\})} &\leq \frac{M_0}{4}, \\
\|\tilde{w}_x\|_{L^\infty([\tau_0, 0])} &\leq b, \\
\tilde{w}(\tau_0-) - \tilde{w}(\tau_0+) &\geq 8\delta_1, \\
\tilde{w}(0-) - \tilde{w}(0+) &\geq 8\delta_2.
\end{aligned}
\]  

(6.18)

Then the Cauchy problem (6.13) with initial data

\[
w(\tau_0, \cdot) = \tilde{w} \in H^2(\mathbb{R}\setminus\{\tau_0, 0\})
\]  

(6.19)

admits a unique entropic solution, defined for \( t \in [\tau_0, 0] \). Moreover, this solution satisfies

\[
\begin{aligned}
\|w(t, \cdot)\|_{H^2(\mathbb{R}\setminus\{0\})} &\leq M_0, \\
\|w_x(t, \cdot)\|_{L^\infty([\tau_0, 0])} &\leq Kb, \\
w(t, t-) - w(t, t+) &\geq \delta_1, \\
w(t, 0-) - w(t, 0+) &\geq \delta_2
\end{aligned}
\]  

(6.20)

for all \( t \in [\tau_0, 0] \).

**Remark 6.1.** By (6.20), at the interaction time \( t=0 \) the solution \( u = w + \varphi^{(w)} \) is the sum of a corrector term plus a function in \( H^2(\mathbb{R}\setminus\{0\}) \). This function lies within the class of initial data covered by our earlier Theorem 2.1. Thus, combining Theorems 6.1 and 2.1 yields the behavior of a solution to (1.1) across the interaction of two shocks.

Toward a proof of Theorem 6.1, solutions to (6.13) will be constructed by an iteration procedure. The main difference between this and the earlier case with a single shock is that the correction term \( \varphi \) now depends on time through the variable strengths \( \sigma_1, \sigma_2 \) of the two shocks. Define

\[
w^{(1)}(t, x) = \begin{cases} 
\tilde{w}(x) & \text{if } x \in [t, 0], \\
\tilde{w}(x + \tau_0 - t) & \text{if } x \in [-\infty, t].
\end{cases}
\]  

(6.21)

By induction, let \( w^{(n)} \) be given and satisfy (6.8) for every \( t \in [\tau_0, 0] \). Moreover, call \( \sigma_1^{(n)}(t) \) and \( \sigma_2^{(n)}(t) \) the strengths of the two shocks at \( x=t \) and \( x=0 \) of \( w^{(n)} \), respectively. We construct the next iterate \( w = w^{(n+1)}(t, x) \) by solving the linear equation

\[
w_t + a(t, x, w^{(n)}) \ w_x = F(t, x, w),
\]  

(6.22)

with initial data (6.19) and \( a \) as introduced in (6.14).

The induction argument requires the following steps:
(i) Given \( w^{(n)} \), \((6.22)\) with the initial data \( \tilde{w} \) admits a unique solution \( w \) with \( w(t, \cdot) \in H^2(\mathbb{R} \setminus \{0\}) \) for all \( t \in [\tau_0, 0] \).

(ii) A priori bounds on the strong norm \( \|w^{(n)}(t, \cdot)\|_{H^2(\mathbb{R} \setminus \{t, 0\})} \) for all \( t \in [\tau_0, 0] \), \( n \geq 1 \).

(iii) Convergence in a weak norm. This will follow from the bound
\[
\sum_{n \geq 1} \|w^{(n+1)}(t, \cdot) - w^{(n)}(t, \cdot)\|_{H^2(\mathbb{R} \setminus \{t, 0\})} < +\infty.
\]

6.1. Some preliminary estimates

To achieve the above steps (i)–(iii), we first establish some key estimates on the right hand side of (6.13). For any \( w : [\tau_0, 0] \times \mathbb{R} \rightarrow \mathbb{R} \) such that \( w(t, \cdot) \in H^2(\mathbb{R} \setminus \{t, 0\}) \) for all \( t \in [\tau_0, 0] \), we write
\[
w(t, \cdot) = v_1(t, \cdot) + v_2(t, \cdot)
\]

with
\[
v_2(t,x) = \begin{cases} (w(t,0-)+x \cdot w_x(t,0-)) \cdot \eta(x) & \text{if } x < 0, \\ (w(t,0+)+x \cdot w_x(t,0+)) \cdot \eta(x) & \text{if } x > 0. \end{cases}
\]

Recalling (6.9)–(6.12) and (6.15), we split \( F \) into the four parts:
\[
F(t,x,w) = \frac{1}{a_1^{(w)}(t) - a_2^{(w)}(t)} \cdot \left[ A^{(w)}(t,x) + B^{(w)}(t,x) + C^{(w)}(t,x) + D^{(w)}(t,x) \right].
\]

Here we take
\[
A^{(w)} = H(\varphi^{(w)}) - \varphi_x^{(w)} \varphi_x, \quad B^{(w)} = B^{(v_2)} \overset{\text{def}}{=} H[v_2] - \left( v_2 - \frac{v_2(t,0-)+v_2(t,0+)}{2} \right) \cdot \phi_0(x),
\]
\[
C^{(w)} = \tilde{C}^{(v_1)} \overset{\text{def}}{=} H[v_1] - \left( v_1 - \frac{v_1(t,t-)+v_1(t,t+)}{2} \right) \cdot \phi'_0(x) - t,
\]
\[
D^{(w)} = H[w] - \left( w - a_2^{(w)}(t) \right) \cdot \varphi_x^{(w)} - \left( a_1^{(w)}(t) - a_2^{(w)}(t) \right) \cdot \phi_t^{(w)} - B^{(w)} - C^{(w)}.
\]

**Lemma 6.1.** Let \( w : [\tau_0, 0] \times \mathbb{R} \rightarrow \mathbb{R} \) be such that \( w(t, \cdot) \in H^2(\mathbb{R} \setminus \{t, 0\}) \) for all \( t \in [\tau_0, 0] \), and
\[
\|w(t, \cdot)\|_{H^2(\mathbb{R} \setminus \{t, 0\})} \leq M_0, \quad \|w_x(t,0-)+w_x(t,0+)\| \leq b, \quad \sigma_j^{(w)}(t) \geq \delta_0 > 0.
\]

Moreover, assume that \(-\frac{1}{4}, \min \left\{ 1, \frac{\delta_0^2}{M_0} \right\} < \tau_0 < 0 \) and \( \sigma_j^{(w)}(\cdot) \) is locally Lipschitz on \([\tau_0, 0]\) for \( j = 1, 2 \). Then there is a constant \( C_1 > 0 \), depending only on \( M_0, b, \delta_0 \) such that, for a.e. \( t \in [\tau_0, 0] \) and \( |x| < \frac{1}{2\pi} \) one has
\[
\left\{\begin{array}{l}
|F(t,x,w)| \leq C_1 \cdot \left[ \frac{1 + M_0 + b}{\delta_0} + |\ln |t||
\end{array}\right.
\]

\[
+ \chi_{[\delta,0]}(t) \cdot \frac{|\hat{\sigma}_1^{(w)}(t)| + |\hat{\sigma}_2^{(w)}(t)|}{\delta_0} \cdot \left( |x|^{1/2} + |x - t|^{1/2} \right),
\]

\[
|F_x(t,x,w)| \leq C_1 \cdot \frac{1 + M_0 + b + \chi_{[\delta,0]}(t) \cdot (|\hat{\sigma}_1^{(w)}(t)| + |\hat{\sigma}_2^{(w)}(t)|)}{\delta_0} \cdot (|x|^{-1/2} + |x - t|^{-1/2}).
\]

(6.29)

Furthermore, for every \( \delta > 0 \) sufficiently small one has for all \( t \in [\tau_0,0] \)

\[
\|F(t,x,w)\|_{H^1([\delta,0] \cup [t-\delta,t+\delta])} \leq C_1 \cdot \left[ \frac{1 + M_0 + b + |\hat{\sigma}_1^{(w)}(t)| + |\hat{\sigma}_2^{(w)}(t)|}{\delta_0} \cdot \delta^{-2/3} + |\ln (t)| \right].
\]

(6.30)

**Proof.** We observe that, for all \( t \in [\tau_0,0] \), it holds

\[
a_1^{(w)}(t) - a_2^{(w)}(t) \geq \delta_0 + w(t,t+) - w(t,0-) \geq \delta_0 - M_0 \cdot |t|^{1/2} \geq \frac{\delta_0}{2},
\]

(6.31)

\[
0 < \sigma_j^{(w)}(t) < \sigma_1^{(w)}(t) + \sigma_2^{(w)}(t) = w(t,-t) - w(t,t+) + w(t,0-) - w(t,0+) \leq \left( 2 + \sqrt{|t|} \right) M_0,
\]

\[
\|v_1(t,\cdot)\|_{H^1([\delta,0])}, \|v_2(t,\cdot)\|_{H^1([\delta,0])} \leq \mathcal{O}(1) \cdot (M_0 + b).
\]

According to (6.25), the function \( F \) can be decomposed as the sum of four terms, which will be estimated separately.

1. Recalling (3.2) and (3.10), (6.26) and (6.27) imply that for every \( (t,x) \in [\tau_0,0] \times \left[ -\frac{1}{2\varepsilon}, \frac{1}{2\varepsilon} \right] \) one has

\[
\left\{\begin{array}{l}
|B^{(w)}(t,x)| \leq \mathcal{O}(1) \cdot (M_0 + b), \quad |B_x^{(w)}(t,x)| \leq \mathcal{O}(1) \cdot (M_0 + b) \cdot |\ln |x||^2,
\end{array}\right.
\]

\[
\|B^{(w)}(t,\cdot)\|_{H^1([\delta,0])} \leq \mathcal{O}(1) \cdot (M_0 + b) \cdot \delta^{-2/3}.
\]

(6.32)

and, for every \( (t,x) \in [\tau_0,0] \times \left[ t-\frac{1}{2\varepsilon}, t+\frac{1}{2\varepsilon} \right] \)

\[
\left\{\begin{array}{l}
|C^{(w)}(t,x)| \leq \mathcal{O}(1) \cdot (M_0 + b), \quad |C_x^{(w)}(t,x)| \leq \mathcal{O}(1) \cdot (M_0 + b) \cdot |\ln |x-t||^2,
\end{array}\right.
\]

\[
\|C^{(w)}(t,\cdot)\|_{H^1([\delta,0])} \leq \mathcal{O}(1) \cdot (M_0 + b) \cdot \delta^{-2/3}.
\]

(6.33)

2. Next, we estimate \( A^{(w)} \). Recalling (3.4), i.e.,

\[
g_b(x) = \chi_{[0,\infty]}(x) \cdot \phi(x,b), \quad x \in \mathbb{R}, b \geq 0,
\]

(2.4), and (6.16), we can rewrite, for \( (t,x) \in [\tau_0,0] \times \left[ -\frac{1}{2\varepsilon}, \frac{1}{2\varepsilon} \right] \),

\[
\phi^{(w)}(t,x) = \phi_0(x-t) + \phi_0(x) - \phi_0(t) + E_1^{(w)}(t,x) + E_2^{(w)}(t,x),
\]

(6.34)
Thus, for \((t, x) \in [\tau_0, 0] \times \left[-\frac{1}{2\epsilon}, \frac{1}{2\epsilon}\right]\), Lemma 3.1 and [5, Section 3] imply,
\[
\left\{
\begin{align*}
|H\left[H\left[\varphi^{(w)}(t, \cdot)\right]\right](x)| &\leq \mathcal{O}(1), \\
\left|\frac{d}{dx} H\left[H\left[\varphi^{(w)}(t, \cdot)\right]\right](x)\right| &\leq \mathcal{O}(1) \cdot \left(\ln^2 |x| + \ln^2 |x - t|\right), \\
\|H\left[H\left[\varphi^{(w)}(t, \cdot)\right]\right]\|_{H^2(\mathbb{R} \setminus (-\delta, \delta)] \cup [t-\delta, t+\delta])} &\leq \mathcal{O}(1) \cdot \delta^{-2/3}.
\end{align*}
\right.
\]
(6.36)

On the other hand, given \(t \in [\tau_0, 0]\), for every \(|x| \leq \frac{1}{2\epsilon}\), (6.34) combined with (3.5) yields
\[
|\varphi^{(w)}(t, x)| \leq \min(|x \ln |x||, |(x - t) \ln |x - t||).
\]
Furthermore, we compute for every \(x \in \mathbb{R} \setminus \{t, 0\}\)
\[
\varphi^{(w)}_x(t, x) = \left(1 - \frac{2 \cdot \chi_{[0, \infty]} \cdot \sigma_2^{(w)}(t)}{\sigma_1^{(w)}(t) + 2 \sigma_2^{(w)}(t)}\right) \varphi_0(x - t) + \left(1 - \frac{2 \cdot \chi_{[-\infty, 0]} \cdot \sigma_1^{(w)}(t)}{2 \sigma_1^{(w)}(t) + \sigma_2^{(w)}(t)}\right) \cdot \varphi_0(x),
\]
(6.37)
which together with [5, Section 3] implies for \(|x| \leq \frac{1}{2\epsilon}\) that
\[
|\varphi^{(w)}_x(t, x)| \leq \mathcal{O}(1) \cdot (|\ln |x|| + |\ln |x - t||), \quad |\varphi^{(w)}_{xx}(t, x)| \leq \mathcal{O}(1) \cdot \left(\frac{1}{|x|} + \frac{1}{|x - t|}\right), \\
|\varphi^{(w)}_{xxx}(t, x)| \leq \mathcal{O}(1) \cdot \left(\frac{1}{x^2} + \frac{1}{(x - t)^2}\right).
\]

A direct computation yields, for \(|x| \leq \frac{1}{2\epsilon}\),
\[
\left\{
\begin{align*}
\left|\varphi^{(w)} \varphi^{(w)}_x(t, x)\right| &\leq \mathcal{O}(1) \cdot \left(|x|^{1/2} + |x - t|^{1/2}\right), \\
\left|\frac{d}{dx} \left[\varphi^{(w)} \varphi^{(w)}_x\right](t, x)\right| &\leq \mathcal{O}(1) \cdot \left(\ln^2 |x| + \ln^2 |x - t|\right), \\
\left|\frac{d^2}{dx^2} \left[\varphi^{(w)} \varphi^{(w)}_x\right](t, x)\right| &\leq \mathcal{O}(1) \cdot \left(\frac{\ln |x|}{x} + \frac{\ln |x - t|}{x - t}\right).
\end{align*}\right.
\]
and thus
\[
\|\varphi^{(w)} \varphi^{(w)}_x(t, \cdot)\|_{H^2(\mathbb{R} \setminus [-\delta, t+\delta] \cup [-\delta, \delta])} \leq \mathcal{O}(1) \cdot \delta^{-2/3}.
\]
Recalling (6.36), we get
Recalling (6.16), we estimate $D_3$. Finally, to estimate $D^{(w)}$, we shall consider three cases:

**Case 1:** Assume that $-\frac{1}{2} < t - \frac{1}{2x} < x < t$. We have

$$D^{(w)}(t,x) = D_1^{(w)}(t,x) + D_2^{(w)}(t,x) + D_3^{(w)}(t,x)$$

with

$$D_1^{(w)}(t,x) = w_x(t,0-) \cdot (t-x) \cdot \phi'_0(x-t),$$

$$D_2^{(w)}(t,x) = \frac{\sigma_1^{(w)}(t) \cdot |w(t,0-) - w(t,t+)| + w(t,t-) - w(t,x)|}{2\sigma_1^{(w)}(t) + \sigma_2^{(w)}(t)} \cdot \phi'_0(x),$$

$$D_3^{(w)}(t,x) = \left[ d^{(w)}_2(t) - a^{(w)}_1(t) \right] \cdot \left[ \frac{\sigma_1^{(w)}(t)}{2\sigma_1^{(w)}(t) + \sigma_2^{(w)}(t)} \right] \cdot g_{tt}(t-x) - \frac{\sigma_2^{(w)}(t) \cdot \phi'_0(t)}{2\sigma_1^{(w)}(t) + \sigma_2^{(w)}(t)}.$$

Recalling (6.16), we estimate

$$\left\{ \begin{array}{l}
|D_1^{(w)}(t,x)| \leq O(1) \cdot b \cdot |x-t| |\ln |x-t|| \leq O(1) \cdot b, \\
\frac{|dx| D_1^{(w)}(t,x)}{dx} \leq O(1) \cdot b \cdot |\ln |x-t||, \\
\frac{|dx|^2 D_1^{(w)}(t,x)}{dx^2} \leq O(1) \cdot b \cdot |\ln |x-t||,
\end{array} \right.$$  

$$\left\{ \begin{array}{l}
|D_2^{(w)}(t,x)| \leq O(1) \cdot (M_0 + b) \cdot |x| |\ln |x||, \\
\frac{|dx| D_2^{(w)}(t,x)}{dx} \leq O(1) \cdot (M_0 + b) \cdot |\ln |x||, \\
\frac{|dx|^2 D_2^{(w)}(t,x)}{dx^2} \leq |w_{xx} \cdot \phi'_0(x)| + O(1) \cdot \frac{M_0 + b}{|x|},
\end{array} \right.$$  

and

$$\left\{ \begin{array}{l}
|D_3^{(w)}(t,x)| \leq O(1) \cdot \left| a^{(w)}_2(t) - a^{(w)}_1(t) \right| \cdot \left( \frac{|\sigma_1^{(w)}(t)| + |\sigma_2^{(w)}(t)|}{\delta_0} |x-t| |\ln |x-t|| + |\ln |t|| \right), \\
\frac{|dx| D_3^{(w)}(t,x)}{dx} \leq O(1) \cdot \left| a^{(w)}_2(t) - a^{(w)}_1(t) \right| \cdot \left( \frac{|\sigma_1^{(w)}(t)| + |\sigma_2^{(w)}(t)|}{\delta_0} \cdot |\ln |x-t||, \\
\frac{|dx| D_3^{(w)}(t,x)}{dx^2} \leq O(1) \cdot \left| a^{(w)}_2(t) - a^{(w)}_1(t) \right| \cdot \left( \frac{|\sigma_1^{(w)}(t)| + |\sigma_2^{(w)}(t)|}{\delta_0} \cdot \frac{1}{|x-t|} \right).
\end{array} \right.$$  

Combining (6.39)--(6.42), we obtain
\[
\begin{align*}
&\frac{|D^{(w)}(t,x)|}{a_2^{(w)}(t) - a_1^{(w)}(t)} \leq \mathcal{O}(1) \cdot \left( M_0 + b + \frac{|\dot{\sigma}_1^{(w)}(t)|}{\delta_0} + \frac{|\dot{\sigma}_2^{(w)}(t)|}{\delta_0} \cdot |x - t|^{1/2} \right), \\
&\frac{d}{dx} D^{(w)}(t,x) \leq \mathcal{O}(1) \cdot \frac{M_0 + b + |\dot{\sigma}_1^{(w)}(t)|}{\delta_0} \cdot |\ln |x| - t||, \\
&\frac{d^2}{dx^2} D^{(w)}(t,x) \leq \mathcal{O}(1) \cdot \frac{M_0 + b + |\dot{\sigma}_1^{(w)}(t)|}{\delta_0} \cdot \left( |\ln |x|| + |\ln |x - t|| \right), \\
&\frac{a_2^{(w)}(t) - a_1^{(w)}(t)}{a_2^{(w)}(t) - a_1^{(w)}(t)} \leq \mathcal{O}(1) \cdot \left( M_0 + b + \frac{|\dot{\sigma}_1^{(w)}(t)|}{\delta_0} + \frac{|\dot{\sigma}_2^{(w)}(t)|}{\delta_0} \cdot \left( |\ln |x|| + |\ln |x - t|| \right) \right).
\end{align*}
\]

**Case 2:** Assume that \( t < x < 0 \). We have

\[
D^{(w)}(t,x) = w_x(t,0-) \cdot (t - x) \cdot \phi_0(x - t) + (v_1(t,0) - v_1(t,x)) \cdot \phi_0(x) + \left[ a_1^{(w)}(t) - a_2^{(w)}(t) \right] \cdot \phi_0(t),
\]

and this yields

\[
\begin{align*}
&\frac{|D^{(w)}(t,x)|}{a_2^{(w)}(t) - a_1^{(w)}(t)} \leq \mathcal{O}(1) \left( M_0 + b + \ln |t| \right), \\
&\frac{d}{dx} D^{(w)}(t,x) \leq \mathcal{O}(1) \cdot \frac{M_0 + b}{\delta_0} \cdot (|\ln |x|| + |\ln |x - t||), \\
&\frac{d^2}{dx^2} D^{(w)}(t,x) \leq \mathcal{O}(1) \cdot \left( \frac{M_0 + b}{\delta_0} \cdot \left( \frac{1}{|x|} + \frac{1}{|x - t|} \right) \right) + \frac{|w_{xx}(t,x)|}{\delta_0} \cdot |\ln |x||.
\end{align*}
\]

**Case 3:** Assume that \( 0 < x < 1/2 \). As in Case 1, writing

\[
D^{(w)}(t,x) = D_1^{(w)}(t,x) + D_2^{(w)}(t,x) + D_3^{(w)}(t,x)
\]

with

\[
\begin{align*}
D_1^{(w)}(t,x) &= \left[ v_1(t,x) - v_1(t,t+) \right] \cdot \phi_0^\prime(x - t) \\
&\quad + \left[ \frac{\sigma_1^{(w)}(t)}{\sigma_1^{(w)}(t) + 2\sigma_2^{(w)}(t)} \cdot \left( w(t,t+) - w(t,0-) + w(t,0+) - w(t,x) \right) \right] \cdot \phi_0^\prime(x - t), \\
D_2^{(w)}(t,x) &= \left( w(t,0+) - w(t,x) + x w_x(t,0+) \right) \cdot \phi_0^\prime(x), \\
D_3^{(w)}(t,x) &= \left[ a_2^{(w)}(t) - a_1^{(w)}(t) \right] \cdot \left[ \frac{\sigma_1^{(w)}(t)}{\sigma_1^{(w)}(t) + 2\sigma_2^{(w)}(t)} \right] \cdot \phi_0^\prime(x) - \frac{\sigma_1^{(w)}(t)}{\sigma_1^{(w)}(t) + 2\sigma_2^{(w)}(t)} \cdot \phi_0^\prime(t),
\end{align*}
\]

we estimate
Lemma 6.2. Let \( w \) be approximations inductively defined by (6.22). Moreover, assume that there exists a function \( K(t) \) such that

\[
\max \left\{ \left| \dot{\sigma}_1(w)(t) \right|, \left| \dot{\sigma}_2(w)(t) \right| \right\} \leq K(t) \quad \text{a.e. } t \in [\tau_0, 0].
\]

Set \( z = w_2 - w_1 \), \( \sigma_i(z) = \dot{\sigma}_i(w_2) - \dot{\sigma}_i(w_1) \), and \( \gamma(z)(t) = \max \left\{ \left| \dot{\sigma}_1(z)(t) \right|, \left| \dot{\sigma}_2(z)(t) \right| \right\} \). Furthermore, let

\[
\frac{|D^{(w)}(t,x)|}{|a_2^{(w)}(t) - a_1^{(w)}(t)|} \leq O(1) \cdot \left( \frac{M_0 + b + \left| \dot{\sigma}_1^{(w)}(t) \right| + \left| \dot{\sigma}_2^{(w)}(t) \right|}{\delta_0} \cdot \ln |x| \right),
\]

\[
\frac{d}{dx} D^{(w)}(t,x) \leq O(1) \cdot \frac{M_0 + b + \left| \dot{\sigma}_1^{(w)}(t) \right| + \left| \dot{\sigma}_2^{(w)}(t) \right|}{\delta_0} \cdot \ln |x|.
\]

In summary, from (6.43), (6.45), and (6.47), given \( t \in [\tau_0, 0] \), for every \( x \in (-1/2, 1/2) \), it holds that

\[
\frac{|D^{(w)}(t,x)|}{|a_2^{(w)}(t) - a_1^{(w)}(t)|} \leq O(1) \cdot \left( \frac{M_0 + b + \left| \dot{\sigma}_1^{(w)}(t) \right| + \left| \dot{\sigma}_2^{(w)}(t) \right|}{\delta_0} \cdot \ln |x| \right),
\]

\[
\frac{d}{dx} D^{(w)}(t,x) \leq O(1) \cdot \frac{M_0 + b + \left| \dot{\sigma}_1^{(w)}(t) \right| + \left| \dot{\sigma}_2^{(w)}(t) \right|}{\delta_0} \cdot \ln |x|.
\]

To complete the proof, combining (6.32), (6.33), (6.38) and (6.48), we obtain (6.29)–(6.30). \( \square \)

The next lemma estimates the change in the function \( F = F(t,x,w) \) as \( w(\cdot) \) takes different values. These estimates will play a key role in the proof of convergence of the approximations inductively defined by (6.22).

Lemma 6.2. Let \( w_1, w_2 : [\tau_0, 0] \times \mathbb{R} \to \mathbb{R} \) be such that, for \( i \in \{1,2\} \) and \( t \in [\tau_0, 0] \), one has \( w_i(t, \cdot) \in H^2(\mathbb{R} \setminus \{0\}) \) and

\[
\|w_i(t, \cdot)\|_{H^2(\mathbb{R} \setminus \{0\})} \leq M_0, \quad \|w_i, x(t,0-)| + |w_i, x(t,0+)| \leq b, \quad \left| \sigma_j^{(w)}(t) \right| \geq \delta_0.
\]

Moreover, assume that \(-\frac{1}{4} \cdot \min \{1, \frac{\delta_0}{H^2} \} < \tau_0 < 0 \) and \( \sigma_j^{(w)} \) is locally Lipschitz on \([\tau_0, 0[\) and there exists a function \( K(t) \) such that

\[
\max \left\{ \left| \dot{\sigma}_1^{(w)}(t) \right|, \left| \dot{\sigma}_2^{(w)}(t) \right| \right\} \leq K(t) \quad \text{a.e. } t \in [\tau_0, 0].
\]
Then there exists a constant $C_2 > 0$, depending only on $M_0$, $b$, $\delta_0$ such that, for every $x \in [-\frac{1}{2\varepsilon}, \frac{1}{2\varepsilon}]$ and a.e. $t \in [\tau_0, 0]$, one has

$$|F(t, x, w_2) - F(t, x, w_1)| \leq \frac{C_2}{\delta_0} \cdot (M_0 + b) \cdot \gamma(t) \cdot (|x|^{1/2} \chi_{[0, \infty]} + |x - t|^{1/2} \chi_{[-\infty, t]})$$

$$+ \frac{C_2}{\delta_0^2} \cdot M_2(t) \cdot (| \ln |t|| + \frac{M_0 + b + K(t)}{\delta_0} \cdot (|x|^{1/2} + |x - t|^{1/2}))$$

(6.49)

and for every $x \in (t, 0)$

$$|F_x(t, x, w_2) - F_x(t, x, w_1)| \leq \frac{C_2}{\delta_0} \cdot M_2(t) \cdot \left(1 + \delta_0 + M_0 + b\right)(|x|^{-1/2} + |x - t|^{-1/2})$$

(6.50)

Moreover, for every $\delta > 0$ sufficiently small, it holds

$$\|F(t, \cdot, w_2) - F(t, \cdot, w_1)\|_{H^2([\tau_0, 0])} \leq \frac{C_2}{\delta_0} \cdot (M_0 + b) \cdot \gamma(t) \cdot \delta^{-2/3}$$

$$+ \frac{C_2}{\delta_0^2} \cdot M_2(t) \cdot \left(\frac{K(t) + M_0 + b + 1}{\delta_0} + M_0 + b + 1\right) \cdot \delta^{-2/3} + | \ln |t||$$

(6.51)

**Proof.**

1. For notational convenience, we set

$$A^{(z)} = A^{(w_2)} - A^{(w_1)}, \quad B^{(z)} = B^{(w_2)} - B^{(w_1)}, \quad C^{(z)} = C^{(w_2)} - C^{(w_1)}, \quad D^{(z)} = D^{(w_2)} - D^{(w_1)}.$$  

(6.52)

Furthermore, let $z_j = v_{1,j} - v_{2,j}$ for $j = 1, 2$, then

$$\|z_1(t, \cdot)\|_{H^2([\tau_0, 0], \Omega)} \leq O(1) \cdot M_2(t), \quad \|z_2(t, \cdot)\|_{H^2([\tau_0, 0], \Omega)} \leq O(1) \cdot M_2(t).$$

Comparing (3.2) and (6.26) and recalling (3.20), then yields, for every $(t, x) \in [\tau_0, 0] \times [-\frac{1}{2\varepsilon}, \frac{1}{2\varepsilon}]$,

$$\begin{align*}
|B^{(z)}(t, x)| = O(1) \cdot M_2(t), & \quad |B^{(z)}_x(t, x)| = O(1) \cdot M_2(t) \cdot |\ln |x||^2, \\
\|B^{(z)}(\cdot, \cdot)\|_{H^2([\tau_0, 0], \Omega)} \leq O(1) \cdot \frac{M_2(t)}{\delta^{2/3}}.
\end{align*}$$

(6.53)

Similarly, for every $(t, x) \in [\tau_0, 0] \times [t - \frac{1}{2\varepsilon}, t + \frac{1}{2\varepsilon}]$, it holds

$$\begin{align*}
|C^{(z)}(t, x)| = O(1) \cdot M_2(t), & \quad |C^{(z)}_x(t, x)| = O(1) \cdot M_2(t) \cdot |\ln |x - t||^2, \\
\|C^{(z)}(\cdot, \cdot)\|_{H^2([\tau_0, 0], \Omega)} \leq O(1) \cdot \frac{M_2(t)}{\delta^{2/3}}.
\end{align*}$$

(6.54)
2. We now provide bounds on $A^{(z)}(t,x)$. From (6.34) and (6.35), it follows that

$$
\varphi^{(w_2)}(t,x) - \varphi^{(w_1)}(t,x) = \left[ \frac{2\sigma_1^{(w_1)}(t)}{2\sigma_1^{(w_1)}(t) + \sigma_2^{(w_1)}(t)} - \frac{2\sigma_1^{(w_2)}(t)}{2\sigma_1^{(w_2)}(t) + \sigma_2^{(w_2)}(t)} \right] \cdot g_{|t|}(t-x) \\
+ \left[ \frac{2\sigma_2^{(w_1)}(t)}{\sigma_1^{(w_1)}(t) + 2\sigma_2^{(w_1)}(t)} - \frac{2\sigma_2^{(w_2)}(t)}{\sigma_1^{(w_2)}(t) + 2\sigma_2^{(w_2)}(t)} \right] \cdot g_{|t|}(x).
$$

Since

$$
\begin{align*}
\begin{cases}
\left| H[\varphi^{(w_2)}(t,x) - \varphi^{(w_1)}(t,x)] \right| & \leq O(1) \cdot \frac{M_2(t)}{\delta_0}, \\
\left| \frac{d}{dx} H[\varphi^{(w_2)}(t,x) - \varphi^{(w_1)}(t,x)] \right| & \leq O(1) \cdot \frac{M_2(t)}{\delta_0} \cdot (\ln^2|x| + \ln^2|x-t|), \\
\left\| H[\varphi^{(w_2)}(t,\cdot) - \varphi^{(w_1)}(t,\cdot)] \right\|_{H^2(\mathbb{R} \setminus [t-\delta, t+\delta] \cup (-\delta, \delta))} & \leq O(1) \cdot \frac{M_2(t)}{\delta_0} \cdot \delta^{-2/3}.
\end{cases}
\end{align*}
$$

Lemma 3.1 implies for $x \notin \{t,0\}$ and $|x| \leq \frac{1}{2\delta}$,

$$
\begin{align*}
\begin{cases}
\left| \varphi^{(w_2)} \varphi_x^{(w_1)} - \varphi^{(w_1)} \varphi_x^{(w_1)} \right| & \leq O(1) \cdot \frac{M_2(t)}{\delta_0} \cdot (|x|^{1/2} + |x-t|^{1/2}), \\
\left| \frac{d}{dx} \left( \varphi^{(w_2)} \varphi_x^{(w_2)} - \varphi^{(w_1)} \varphi_x^{(w_1)} \right) \right| & \leq O(1) \cdot \frac{M_2(t)}{\delta_0} \cdot (\ln^2|x| + \ln^2|x-t|), \\
\left| \frac{d^2}{dx^2} \left( \varphi^{(w_2)} \varphi_x^{(w_2)} - \varphi^{(w_1)} \varphi_x^{(w_1)} \right) \right| & \leq O(1) \cdot \frac{M_2(t)}{\delta_0} \cdot \left( \frac{|\ln |x||}{|x|} + \frac{|\ln |x-t||}{|x-t|} \right), \\
\left\| \varphi^{(w_2)} \varphi_x^{(w_2)} - \varphi^{(w_1)} \varphi_x^{(w_1)} \right\|_{H^2(\mathbb{R} \setminus [t-\delta, t+\delta] \cup (-\delta, \delta))} & \leq O(1) \cdot \frac{M_2(t)}{\delta_0} \cdot \delta^{-2/3}.
\end{cases}
\end{align*}
$$

Thus, (6.26) yields

$$
\begin{align*}
\begin{cases}
|A^{(z)}(t,x)| & \leq O(1) \cdot \frac{M_2(t)}{\delta_0}, \\
|A^{(z)}_x(t,x)| & \leq O(1) \cdot \frac{M_2(t)}{\delta_0} \cdot (\ln^2|x| + \ln^2|x-t|), \\
\left\| A^{(z)}(t,\cdot) \right\|_{H^2(\mathbb{R} \setminus [t-\delta, t+\delta] \cup (-\delta, \delta))} & \leq O(1) \cdot \frac{M_2(t)}{\delta_0} \cdot \delta^{-2/3}.
\end{cases}
\end{align*}
$$

(6.56)

3. Finally, to achieve bound on $D^{(z)}$, we consider three cases as in the proof of Lemma 6.1. As before, we define $D_i^{(z)} = D_i^{(w_2)} - D_i^{(w_1)}$ for $i = 1, 2, 3$. 

---

COMMUNICATIONS IN PARTIAL DIFFERENTIAL EQUATIONS
Case 1: Assume that $-1/2 < t - \frac{1}{2c} < x < t$. Note, that we can write

$$
\begin{align*}
\mathbf{D}^{(z)}(t, x) &= \mathbf{D}_1^{(z)}(t, x) + \mathbf{D}_2^{(z)}(t, x) + \mathbf{D}_3^{(z)}(t, x) \\
\mathbf{D}_1^{(z)}(t, x) &= I_1^{(z)}(t, x) \cdot \phi_0'(x - t), \\
\mathbf{D}_2^{(z)}(t, x) &= I_2^{(z)}(t, x) \cdot \phi_0'(x), \\
\mathbf{D}_3^{(z)}(t, x) &= I_{31}^{(z)}(t) \cdot g_{\left(1\right)}(t - x) + I_{32}^{(z)}(t) \cdot \phi_0'(t),
\end{align*}
$$

which implies

$$
\begin{align*}
\left| I_1^{(z)}(t, x) \right| &\leq \mathcal{O}(1) \cdot M_2(t) \cdot |t - x|, \\
\left| \partial_x I_1^{(z)}(t, x) \right| &\leq \mathcal{O}(1) \cdot M_1(t), \\
\left| \partial_{xx} I_1^{(z)}(t, x) \right| &\leq \mathcal{O}(1) \cdot \left( \frac{M_0 + b}{\delta_0} \cdot M_2(t) \cdot |z_x(t, x)| \right), \\
\left| \partial_{xx} I_2^{(z)}(t, x) \right| &\leq \mathcal{O}(1) \cdot \left( \frac{|w_{2,xx}(t, x)|}{\delta_0} \cdot M_2(t) \cdot |z_{xx}(t, x)| \right), \\
\left| I_{31}^{(z)}(t) \right| &\leq \mathcal{O}(1) \cdot \left( \frac{K(t) \left( 1 + \delta_0 \right) M_2(t) + \frac{M_0 \cdot \gamma^{(z)}(t)}{\delta_0}}{\delta_0} \right), \\
\left| I_{32}^{(z)}(t) \right| &\leq \mathcal{O}(1) \cdot \frac{M_0 M_2(t)}{\delta_0}.
\end{align*}
$$

Thus, for $t > 0$ sufficiently small such that $|t| < e^{-M_0 - b}$, it holds

$$
\left| \mathbf{D}^{(z)}(t, x) \right| \leq \mathcal{O}(1) \cdot \left[ \frac{M_0 + b}{\delta_0} \cdot \gamma^{(z)}(t) \cdot |x - t|^{1/2} + \frac{M_2(t)}{\delta_0} \cdot \left( \frac{K(t)}{\delta_0} \cdot |x - t|^{1/2} + (1 + M_0) \cdot |\ln |t|| \right) \right],
$$

and

$$
\begin{align*}
\left| \frac{d}{dx} \mathbf{D}^{(z)}(t, x) \right| &\leq \mathcal{O}(1) \cdot \left[ \frac{M_2(t)}{\delta_0} \cdot \left( \frac{K(t)}{\delta_0} + M_0 + 1 \right) \cdot |x - t|^{1/2} + |z_x(t, x)| \cdot |\ln |x|| \right] \\
&\quad + \mathcal{O}(1) \cdot \left( \frac{M_0 + b}{\delta_0} \cdot \gamma^{(z)}(t) \cdot |\ln |t - x|| \right)
\end{align*}
$$

$$
\begin{align*}
\left| \frac{d^2}{d^2 x} \mathbf{D}^{(z)}(t, x) \right| &\leq \mathcal{O}(1) \cdot \left[ \frac{M_2(t)}{\delta_0} \cdot \left( \frac{K(t)}{\delta_0} + M_0 + 1 \right) \cdot \frac{1}{|x - t|} + |w_{2,xx}(t, x)| \cdot |\ln |x|| \right] \\
&\quad + \mathcal{O}(1) \cdot \left[ |z_{xx}(t, x)| \cdot |\ln |x|| + \frac{M_0 + b}{\delta_0} \cdot \gamma^{(z)}(t) \cdot \frac{1}{|x - t|} \right].
\end{align*}
$$

Case 2: Assuming $t < x < 0$, we have

$$
\mathbf{D}^{(z)}(t, x) = z_x(t, 0-) \cdot (t - x) \cdot \phi_0'(x - t) + (z_1(t, 0) - z_1(t, x)) \cdot \phi_0'(x) + \left[ a_1^{(z)}(t) - a_2^{(z)}(t) \right] \cdot \phi_0'(t),
$$

with

$$
a_j^{(z)}(t) = a_j^{(w_2)}(t) - a_j^{(w_1)}(t),
$$
which yields
\[
\begin{align*}
\left| \frac{d}{dx} D^{(z)}(t, x) \right| & \leq O(1) \cdot M_2(t) \cdot |\ln |t||, \\
\frac{d}{dx} D^{(z)}(t, x) & \leq O(1) \cdot \left[ M_2(t) \cdot |x|^{-1/2} + |z_{1,x}(t, x)| \cdot |\ln |x|| \right], \\
\left| \frac{d^2}{dx^2} D^{(z)}(t, x) \right| & \leq O(1) \cdot \left[ M_2(t) \cdot \left( \frac{1}{|x|} + \frac{1}{|x-t|} \right) + |z_{1,xx}(t, x)| \cdot |\ln |x|| \right].
\end{align*}
\]

**Case 3:** Assume that \( 0 < x < 1/2 \) and \(|t| \leq e^{-M_0-b} \). As in Case 1, we estimate
\[
\left| D^{(z)}(t, x) \right| \leq O(1) \cdot \left[ M_2(t) \cdot \left( \frac{K(t)(M_0 + \delta_0) \cdot x^{1/2}}{\delta_0} + (1 + M_0) |\ln |t|| \right) \\
+ \frac{M_0 + b}{\delta_0} \cdot \gamma^{(z)}(t) \cdot x^{1/2} \right]
\]

and
\[
\begin{align*}
\left| \frac{d}{dx} D^{(z)}(t, x) \right| & \leq O(1) \cdot \left[ M_2(t) \cdot \left( \frac{K(t)(M_0 + \delta_0) \cdot x^{1/2}}{\delta_0} + M_0 + b + 1 \right) \cdot |x|^{-1/2} \right] \\
& \quad + O(1) \cdot \left[ |z_{1,x}(t, x)| + |z_{1,xx}(t, x)| \cdot |\ln |x|| \right] + \frac{M_0 + b}{\delta_0} \cdot \gamma^{(z)}(t) \cdot \frac{1}{|x|} \\
\left| \frac{d^2}{dx^2} D^{(z)}(t, x) \right| & \leq O(1) \cdot \left[ \left( \frac{K(t)(M_0 + \delta_0) \cdot x^{1/2}}{\delta_0} + M_0 + b + 1 \right) \cdot \frac{1}{|x|} + |z_{2,xx}(t, x)| \cdot |\ln |x-t|| \right].
\end{align*}
\]

In summary, given \( t \in [\tau_0, 0] \) sufficiently small, for every \( x \in (-1/2, 1/2) \setminus \{t, 0\} \), it holds that
\[
\begin{align*}
\left| D^{(z)}(t, x) \right| & \leq O(1) \cdot \left[ M_2(t) \cdot (1 + M_0) \cdot |\ln |t|| \\
& \quad + \frac{M_2(t)K(t)}{\delta_0} + M_2(t) + \frac{M_0 + b}{\delta_0} \cdot \gamma^{(z)}(t) \cdot \left( |x|^{1/2} \chi_{[0, \infty]} + |x-t|^{1/2} \chi_{(-\infty, t]} \right) \right], \\
\left| \frac{d}{dx} D^{(z)}(t, x) \right| & \leq O(1) \cdot \left( \frac{M_0 + b}{\delta_0} \cdot \gamma^{(z)}(t) \cdot \left( |x|^{-1/4} \chi_{[0, \infty]} + |x-t|^{-1/4} \chi_{(-\infty, t]} \right) \right) \\
& \quad + \frac{M_2(t)K(t)}{\delta_0} + M_0 + b + 1 \right) \cdot |z_{1,x}(t, x)| \cdot (|x|^{-1/2} + |x-t|^{-1/2}) \\
\left| \frac{d^2}{dx^2} D^{(z)}(t, x) \right| & \leq O(1) \cdot \left[ \frac{M_2(t)}{\delta_0} \cdot \left( \frac{K(t) + M_0 + b + 1}{\delta_0} \right) \cdot \delta^{-2/3} + |\ln |t|| \right] \\
& \quad + O(1) \cdot \left( \frac{M_0 + b}{\delta_0} \cdot \gamma^{(z)}(t) \cdot \delta^{-2/3} \right). \\
\end{align*}
\]

Finally, combining (6.25)–(6.28), Lemma 6.1, and (6.52)–(6.57), we obtain (6.49)–(6.51) \( \square \)
6.2. Proof of Theorem 6.1

We are now ready to give a proof of Theorem 6.1. Given \( \tau_0 \in [-\varepsilon_0, 0] \) sufficiently small and some initial data \( w(\tau_0, \cdot) = \bar{w} \) satisfying (6.18), we construct a solution to the Cauchy problem (6.13). This solution will be obtained as the limit of a Cauchy sequence of approximate solutions \( w^{(n)}(t, x) \), following the steps (i)–(iii) outlined in the beginning of Section 6.

**Step 1.** Let \( b, M_0, \delta_1, \delta_2 > 0 \) and \( \bar{w} \in H^2(\mathbb{R} \setminus \{\tau_0, 0\}) \) such that

\[
\begin{align*}
\|\bar{w}\|_{H^2(\mathbb{R} \setminus \{\tau_0, 0\})} & \leq \frac{M_0}{4}, \\
\|\bar{w}_x\|_{L^\infty([t, 0])} & \leq b, \\
\bar{w}(\tau_0-) - \bar{w}(\tau_0+) & = 8\delta_1, \\
\bar{w}(0-) - \bar{w}(0+) & = 8\delta_2.
\end{align*}
\]

(6.58)

We first establish the existence and uniqueness of solutions to the linear problem (6.22) with initial data \( \bar{w} \) and a given function \( w^{(n)} \) with \( w^{(n)}(t, \cdot) \in H^2(\mathbb{R} \setminus \{t, 0\}) \) for all \( t \in [\tau_0, 0] \) and such that for all \( t \in [\tau_0, 0] \),

\[
\begin{align*}
\|w^{(n)}(t, \cdot)\|_{H^2(\mathbb{R} \setminus \{t, 0\})} & \leq M_0, \\
\|w^{(n)}_x(t, x)\|_{L^\infty([t, 0])} & \leq Kb, \\
|w^{(n)}(t, t \pm) - \bar{w}(\tau_0 \pm)| & \leq \delta_1, \\
|w^{(n)}(t, 0 \pm) - \bar{w}(0 \pm)| & \leq \delta_2,
\end{align*}
\]

(6.59)

for some constant \( K > 0 \) depending only on \( b, M_0, \delta_1, \delta_2 \). Note that \( w^{(1)} \), defined in (6.21), satisfies all of these assumptions.

Note that if such a sequence exist, then the constant \( \delta_0 \) in Lemma 6.1 and Lemma 6.2 can be chosen as \( \min(\delta_1, \delta_2) \). Accordingly, we define

\[ \delta_0 \doteq \min(\delta_1, \delta_2). \]

Assume

\[ -\frac{1}{4} \cdot \min\left\{ \frac{\delta_1^2, \delta_2^2}{M_0^2} \right\} < \tau_0 < 0, \]

(6.60)

and denote by \( t \mapsto x(t; t_0, x_0) \) the solution to the Cauchy problem

\[ \dot{x}(t) = a_n(t, x(t)), \quad x(t_0) = x_0, \]

(6.61)

where

\[ a_n(t, x) \doteq \frac{w^{(n)}(t, x) + \phi^{(n)}(t, x) - a_2^{(n)}(t)}{a_1^{(n)}(t) - a_2^{(n)}(t)}. \]

(6.62)

Here,

\[ \phi^{(n)}(t, x) \doteq \phi^{(w^{(n)})}(t, x), \quad a_j^{(n)}(t) = a_j^{(w^{(n)})}(t), \quad \sigma_j^{(n)}(t) = \sigma_j^{(w^{(n)})}(t) \quad \text{for } j = 1, 2. \]

(6.63)

To begin with we study the travel direction of \( x(t) \), which depends on the sign of \( a_n \). Therefore, observe that (6.58) and (6.59) imply
\[ 6\delta_i \leq \sigma_i^{(n)}(t) \leq 10\delta_i \quad t \in [\tau_0, 0[, i \in \{1, 2\}. \quad (6.64) \]

Furthermore,
\[
\left| a_1^{(n)}(t) - a_2^{(n)}(t) - \frac{1}{2} \cdot \left( \sigma_1^{(n)}(t) + \sigma_2^{(n)}(t) \right) \right| = \left| w^{(n)}(t, t+) - w^{(n)}(t, 0-) \right| \leq M_0 \sqrt{|t|},
\]
and
\[
3(\delta_1 + \delta_2) - M_0 \sqrt{|t|} \leq \left| a_1^{(n)}(t) - a_2^{(n)}(t) \right| \leq 5(\delta_1 + \delta_2) + M_0 \sqrt{|t|}.
\]

Recalling (6.60) we end up with
\[
2(\delta_1 + \delta_2) \leq \left| a_1^{(n)}(t) - a_2^{(n)}(t) \right| \leq 6(\delta_1 + \delta_2). \quad (6.65)
\]

For every \((t, x) \in [\tau_0, 0[ \times ]0, 1/2[, \) one has, using (6.17), (6.35), and (3.5),
\[
\left| a_n(t, x) + \frac{\sigma_2^{(n)}(t)}{2(a_1^{(n)}(t) - a_2^{(n)}(t))} \right| = \left| \frac{w^{(n)}(t, x) - w^{(n)}(t, 0+) + \varphi^{(n)}(t, x)}{a_1^{(n)}(t) - a_2^{(n)}(t)} \right|
\leq \frac{1}{2(\delta_1 + \delta_2)} \cdot \left( \left| w^{(n)}(t, x) - w^{(n)}(t, 0+) \right| + |\varphi^{(n)}(t, x)| \right)
\leq \frac{1}{2(\delta_1 + \delta_2)} \cdot (M_0 x^{1/2} + 2|x \ln x|).
\]

Similarly, for every \((t, x) \in [\tau_0, 0[ \times ]1/2, t[, \)
\[
\left| a_n(t, x) - 1 - \frac{\sigma_1^{(n)}(t)}{2(a_1^{(n)}(t) - a_2^{(n)}(t))} \right| = \left| \frac{w^{(n)}(t, x) - w^{(n)}(t, t-) + \varphi^{(n)}(t, x)}{a_1^{(n)}(t) - a_2^{(n)}(t)} \right|
\leq \frac{1}{2(\delta_1 + \delta_2)} \cdot (M_0 \cdot |x - t|^{1/2} + 2 \cdot |x - t| \ln |x - t|), \quad (6.67)
\]
and for any \((t, x) \in [\tau_0, 0[ \times ]t, 0[, \)
\[
\left| a_n(t, x) - 1 + \frac{\sigma_1^{(n)}(t)}{2(a_1^{(n)}(t) - a_2^{(n)}(t))} \right| = \left| \frac{w^{(n)}(t, x) - w^{(n)}(t, t+) + \varphi^{(n)}(t, x)}{a_1^{(n)}(t) - a_2^{(n)}(t)} \right|
\leq \frac{1}{2(\delta_1 + \delta_2)} \cdot (M_0 \cdot |x - t|^{1/2} + 2 \cdot (|x - t| \ln |x - t|) + |x \ln |x||). \quad (6.68)
\]

Since
\[
\begin{align*}
\frac{\sigma_1^{(n)}(t)}{\sigma_1^{(n)}(t) + 10\delta_2 + 2M_0 \sqrt{|t|}} & \leq \frac{\sigma_1^{(n)}(t)}{2(a_1^{(n)}(t) - a_2^{(n)}(t))} \leq \frac{\sigma_1^{(n)}(t)}{\sigma_1^{(n)}(t) + 6\delta_2 + 2M_0 \sqrt{|t|}}, \\
\frac{\sigma_2^{(n)}(t)}{\sigma_2^{(n)}(t) + 10\delta_1 + 2M_0 \sqrt{|t|}} & \leq \frac{\sigma_2^{(n)}(t)}{2(a_1^{(n)}(t) - a_2^{(n)}(t))} \leq \frac{\sigma_2^{(n)}(t)}{\sigma_2^{(n)}(t) + 6\delta_1 + 2M_0 \sqrt{|t|}},
\end{align*}
\]
by (6.64), we conclude, using (6.64) and (6.60) once more, that
Lemma 6.3. We shall prove (6.70) for some $K > 0$ depending only on $M_0, \delta_1, \delta_2, K,$ and $b$.

The next lemma provides the Lipschitz continuous dependence of the characteristic curves (6.69).

Lemma 6.3. Let $w^{(n)}$ and $\varphi^{(n)}$ be as in (6.59) and (6.63). Given $\tau \in [\tau_0, 0[ \cap [\tau_0, 0[ \cap \mathbb{R} \backslash \{0\}$ with $\bar{x}_2 < \bar{x}_1$ such that both $\bar{x}_1$ and $\bar{x}_2$ belong to $\mathbb{R} \setminus \{\bar{x}, \bar{x}_1\}$, then

$$|x(t; \tau, \bar{x}_1) - x(t; \tau, \bar{x}_2)| \leq K_1 \cdot |\bar{x}_2 - \bar{x}_1| \quad \text{for all } t \in [\tau_0, \tau]$$

for some $K_1 > 0$ depending only on $M_0, \delta_1, \delta_2, K,$ and $b$.

Proof. We shall prove (6.70) for $\bar{x}_1, \bar{x}_2 \in [\tau, 0[$. The other cases follow the same lines as the proof of (4.9).

For any $t < x_2 < x_1 < 0$, (6.67) and (6.65) imply

$$|a_n(t, x_2) - a_n(t, x_1)| \leq \frac{1}{2(\delta_1 + \delta_2)} \cdot (Kb + |\ln |x_2 - t|| + |\ln |x_1||) \cdot (x_1 - x_2).$$

Setting $0 \leq z(t) = x(t; \tau, \bar{x}_1) - x(t; \tau, \bar{x}_2)$, we obtain

$$\dot{z}(t) \geq -\frac{1}{2(\delta_1 + \delta_2)} \cdot (Kb + |\ln |x(t; \tau, \bar{x}_2) - t|| + |\ln |x(t; \tau, \bar{x}_1)||) \cdot z(t).$$

Since (6.69) implies for any $\bar{x} \in (0, t)$ that

$$\left(1 - \frac{4\delta_1 + \delta_0}{2(\delta_1 + \delta_2)}\right) (\tau - t) \leq x(t; \tau, \bar{x}) - x(t; \tau, \bar{x}) \leq \left(1 - \frac{2\delta_1 - \delta_0}{2(\delta_1 + \delta_2)}\right) (\tau - t),$$

one ends with

$$\frac{\dot{z}(t)}{z(t)} \geq -\frac{1}{2(\delta_1 + \delta_2)} \cdot \left(Kb + 2 \cdot |\min \left(\frac{\delta_0}{2(\delta_1 + \delta_2)}, \frac{\delta_0}{2(\delta_1 + \delta_2)}\right) (\tau - t)\right)$$

which yields (6.70).
Next, consider the constants
\[ \gamma_0 \doteq \min \left\{ \frac{\delta_0}{2(\delta_1 + 2\delta_2)}, \frac{\delta_0}{2(2\delta_1 + \delta_2)} \right\}, \quad \gamma_1 \doteq \max \left\{ \frac{5\max(\delta_1, \delta_2)}{2(\delta_1 + 2\delta_2)}, \frac{5\max(\delta_1, \delta_2)}{2(2\delta_1 + \delta_2)} \right\}, \]
and define
\[ I^*_t \doteq [t - \gamma_0(t - t), t + \gamma_0(t - t)] \cup [-\gamma_0(t - t), \gamma_0(t - t)]. \]
From (6.69), one has
\[ x(t; \tau, \bar{x}) \not\in I^*_t \quad \text{for all } \tau_0 \leq t < \tau \leq 0, \bar{x} \in [-1/2, 1/2] \setminus \{0, \tau\}. \]
Furthermore, for all \( \tau_0 \leq t < \tau \leq 0 \), one has
\[
\begin{cases}
|\langle x(t; \tau, \bar{x}) - t - (\bar{x} - \tau) \rangle| \leq \gamma_1(t - t), & \bar{x} \in \left[ -\frac{1}{2}, 0 \right] \setminus \{\tau\}, \\
|\langle x(t; \tau, \bar{x}) - \bar{x} \rangle| \leq \gamma_1(t - t), & \bar{x} \in \left[ -\frac{1}{2}, \frac{1}{2} \right] \setminus \{0\}.
\end{cases}
\]

By the same arguments used in [5, Lemma 4.1], we now obtain

**Lemma 6.4.** Let \( w^{(n)} \) and \( \phi^{(n)} \) be as in (6.59) and (6.63). There exists \( \varepsilon_0 > 0 \) small enough, so that for any \( -\varepsilon_0 \leq t < \tau < 0 \) and any solution \( v \) of the linear equation
\[ v_t + a_n(t, x) \cdot v_x = 0, \quad v(\tau_0, \cdot) = \bar{v} \in H^2(\mathbb{R} \setminus I^*_t), \]
on one has
\[ ||v(t, \cdot)||_{H^2(\mathbb{R} \setminus \{\tau_0\})} \leq \frac{3}{2} ||\bar{v}||_{H^2(\mathbb{R} \setminus \{\tau_0\})}. \]

**Step 2.** Let us now consider a sequence of approximate solutions \( w^{(k)} \) to (6.22) inductively defined as follows.

- \( w^{(1)} : [\tau_0, 0] \times \mathbb{R} \rightarrow \mathbb{R} \) such that for all \( t \in [\tau_0, 0] \),
  \[ w^{(1)}(t, x) = \begin{cases} 
  \bar{w}(x) & \text{if } x \in (t, 0) \cup (0, \infty), \\
  \bar{w}(x + \tau_0 - t) & \text{if } x \in (-\infty, t),
  \end{cases} \]
where \( \bar{w} \) satisfies (6.58).
- For every \( k \geq 1 \), \( w^{(k+1)}(t, \cdot) \) solves the linear equation
  \[ w_t + a_n(t, x) \cdot w_x = F^{(k)}(t, x), \quad w(\tau_0, \cdot) = \bar{w}(\cdot) \]
with \( F^{(k)}(t, x) \doteq F(t, x, w^{(k)}) \) and \( \bar{w} \) as in (6.58). This can be rephrased as
\[ w^{(k+1)}(t_0, x_0) = \bar{w}(x(\tau_0; t_0, x_0)) + \int_{\tau_0}^{t_0} F^{(k)}(t, x(t; t_0, x_0)) dt. \]

The following lemma provides a priori estimates on \( w^{(k)} \), uniformly valid for all \( k \geq 1 \).
Lemma 6.5. Let $w^{(n)}$ and $\varphi^{(n)}$ be as in (6.59) and (6.63). Then there exists $\varepsilon_0 > 0$ sufficiently small so that the following holds. If $\tau_0 \in [-\varepsilon_0, 0]$, then for every $k \geq 0$ and a.e. $\tau \in [\tau_0, 0]$, one has

$$
|w^{(k)}(\tau, \tau \pm) - \bar{w}(\tau_0 \pm)| \leq \delta_1, \quad |w^{(k)}(\tau, 0 \pm) - \bar{w}(0 \pm)| \leq \delta_2, \quad (6.76)
$$

$$
\max \left\{ |\dot{\sigma}^{(k)}_1(\tau)|, |\dot{\sigma}^{(k)}_2(\tau)| \right\} \leq 4C_1 |\ln |\tau||, \quad (6.77)
$$

$$
\|w^{(k)}_x(\tau, x)\|_{L^\infty([\tau, 0])} \leq 2K_2 b, \quad \|w^{(k)}(\tau, \cdot)\|_{H^1(\mathbb{R} \setminus \{\tau, 0\})} \leq M_0, \quad (6.78)
$$

for some positive constants $C_1$ and $K_2$.

Proof. It is clear that (6.76)–(6.78) hold for $k=1$. By induction, assume that (6.76)–(6.78) hold for a given $k \geq 1$.

1. We shall establish the first inequality in (6.78). Given $\tau \in [\tau_0, 0]$ and $\tau < \bar{x}_2 < \bar{x}_1 < 0$, consider the characteristics $t \mapsto x_i(t) = x(t; \tau, \bar{x}_i)$ for $i \in \{1, 2\}$, which satisfy, cf. (6.73),

$$
\min \{|x_i(t)|, |x_i(t) - t|\} \geq \gamma_0 \cdot (\tau - t) \quad \text{for all} \ t \in [\tau_0, \tau], i \in \{1, 2\}. \quad (6.79)
$$

Recalling (6.75), (6.70), and (6.29), we estimate

$$
|w^{(k+1)}(\tau, \bar{x}_2) - w^{(k+1)}(\tau, \bar{x}_1)|
\leq |\bar{w}(x_2(\tau_0)) - \bar{w}(x_1(\tau_0))| + \int_{\tau_0}^{\tau} |F^{(k)}(t, x_2(t)) - F^{(k)}(t, x_1(t))| dt
\leq K_1 \cdot \left( b + \frac{C_1(1 + 2M_0 + 2K_2 b)}{\gamma_0^{1/2} \delta_0} \int_{\tau_0}^{\tau} \frac{1}{(\tau - t)^{1/2}} dt \right) \cdot |\bar{x}_2 - \bar{x}_1|
\leq K_1 \cdot \left( b + \frac{2C_1(1 + 2M_0 + 2K_2 b)(\tau - \tau_0)^{1/2}}{\gamma_0^{1/2} \delta_0} \right) \cdot |\bar{x}_2 - \bar{x}_1|.
$$

Thus, if $0 \leq -\tau_0 \leq \left( \frac{\gamma_0^{1/2} \delta_0}{2C_1(1 + 2M_0 + 2K_2 b)} \right)^2$, then

$$
|w^{(k+1)}(\tau, \bar{x}_2) - w^{(k+1)}(\tau, \bar{x}_1)| \leq 2K_2 b \cdot |\bar{x}_2 - \bar{x}_1|
$$

and (6.78) is satisfied by $w^{(k+1)}$.

2. We shall establish (6.77) for $i=2$ and the second inequality in (6.76). The other ones are quite similar. Given any $\tau_0 \leq \tau_1 < \tau_2 \leq 0$, let $t \mapsto x_2^\tau(t) = x(t; \tau_2, 0 \pm)$ be the characteristics, which reach the origin at time $\tau_2$ from the positive and negative side, respectively. From (6.74), it follows that

$$
|x_2^\tau(t)| \leq \gamma_1 \cdot |\tau_2 - t| \quad \text{for all} \ t \in [\tau_1, \tau_2].
$$

Furthermore, recalling (6.77), (6.78), and (6.29), we have
\[ |w^{(k+1)}(\tau_2, 0\pm) - w^{(k+1)}(\tau_1, 0\pm)| \leq |w^{(k+1)}(\tau_1, x_2^+ (\tau_1)) - w^{(k+1)}(\tau_1, 0\pm)| \\
+ \int_{\tau_1}^{\tau_2} |F^{(k)}(t, x_2^+ (t))| dt \leq 2(K_2b + M_0)\gamma_1 \cdot (\tau_2 - \tau_1) \\
+ C_1 \cdot \frac{1 + 2M_0 + 2K_2b}{\delta_0} \\
+ \left(1 + \frac{8C_1}{\delta_0} \frac{2}{\gamma_1} \frac{M_0 + 2K_2b}{\gamma_1} \ln |t| \right) dt \\
\leq \left[ 2(K_2b + M_0)\gamma_1 + \frac{C_1(1 + 2M_0 + 2K_2b)}{\delta_0} \\
+ C_1 \left(1 + \frac{8C_1}{\delta_0} \right) \cdot |\ln |\tau_2|| \right] \cdot (\tau_2 - \tau_1). \]

Thus, for |\tau_0| is sufficiently small, we then obtain (6.77) for (k + 1) and i = 2 by

\[ \left| \sigma_2^{(k+1)}(\tau_2) - \sigma_2^{(k+1)}(\tau_1) \right| \leq 4C_1 |\ln |\tau_2|| \cdot (\tau_2 - \tau_1). \]

Moreover, for the second inequality in (6.76), choose \( \tau_1 = \tau_0 \) in the above estimate, i.e.,

\[ |w^{(k+1)}(\tau_2, 0\pm) - w(0\pm)| \leq \left[ 2(K_2b + M_0)\gamma_1 + \frac{C_1(1 + 2M_0 + 2K_2b)}{\delta_0} \\
+ C_1 \left(1 + \frac{8C_1}{\delta_0} \right) \cdot |\ln |\tau_0|| \right] \cdot |\tau_0|. \]

and this yields (6.76).

3. Finally, from Duhamel’ formula, Lemma 6.4, (6.58), Lemma 6.1, (6.77), and (6.72), we obtain, for all \( t \in [\tau_0, 0] \),

\[ \left\| w^{(k+1)}(\tau, \cdot) \right\|_{H^2(\mathbb{R}\setminus \{t_0\})} \leq \frac{3}{2} \left\| \bar{w} \right\|_{H^2(\mathbb{R}\setminus \{t_0\})} + \frac{3}{2} \int_{t_0}^{t} \left\| F^{(k)}(t, \cdot) \right\|_{H^2(\mathbb{R}\setminus \{t_0\})} dt \\
\leq \frac{3M_0}{8} + \frac{3}{2} C_1 \int_{t_0}^{t} \left\| F^{(k)}(t, \cdot) \right\|_{H^2(\mathbb{R}\setminus \{t_0\})} \left(1 + \frac{2}{\delta_0} \frac{M_0 + 2K_2b + 8C_1 |\ln |\tau_0||}{\gamma_1} \right) \cdot \left| \tau_0 \right|^{1/3} + 3C_1 \cdot |\tau_0| \left| \ln |\tau_0|| \right. \]

Identifying an upper bound on \( \tau_0 \) such that the right hand side is less or equal than \( M_0 \), shows that the second bound in (6.78) is satisfied by \( w^{(k+1)} \) as well.

Thanks to the above estimates, we can now prove that the sequence of approximations \( w^{(k)} \) is Cauchy, and converges to a solution \( w \) of the linear problem (6.22). This will accomplish the inductive step, toward the proof of Theorem 6.1.

Lemma 6.6. There exists \( \varepsilon_0 > 0 \) sufficiently small so that, for all \( \tau_0 \in [-\varepsilon_0, 0] \) the following holds: Let \( w^{(n)}, \phi^{(n)} \) as in (6.59) and (6.63). Then the sequence of approximations \( (w^{(k)}(t, \cdot))_{k \geq 1} \) converges uniformly for all \( t \in [\tau_0, 0] \) to a limit function \( w(t, \cdot) \) in \( H^2(\mathbb{R}\setminus \{t, 0\}) \). Namely,
\[
\lim_{k \to \infty} \sup_{t \in [\tau_0, 0]} \|w^{(k)}(t, \cdot) - w(t, \cdot)\|_{H^2([\tau \cup \{t, 0\})} = 0.
\]

The function \(w\) provides a solution to the Cauchy problem (6.22) and satisfies for all \(\tau \in [\tau_0, 0]\)
\[
|w(\tau, \tau \pm) - \tilde{w}(\tau_0 \pm)| \leq \delta_1, \quad |w(\tau, 0 \pm) - \tilde{w}(0 \pm)| \leq \delta_2, \tag{6.80}
\]
\[
\|w_{x}(\tau, x)\|_{L^{\infty}(\tau, 0)} \leq 2K_2b, \quad \|w(\tau, \cdot)\|_{H^{2}(\{\tau, 0\})} \leq M_0. \tag{6.81}
\]
Moreover, \(\sigma_1(t) \equiv w(t, t-)-w(t, t+)\) and \(\sigma_2(t) \equiv w(t, 0-)-w(t, 0+)\) are locally Lipschitz in \([\tau_0, 0]\) and
\[
\max\{\|\hat{\sigma}_1(\tau)\|, \|\hat{\sigma}_2(\tau)\|\} \leq 4C_1|\ln \tau| \quad \mathrm{a.e.} \quad \tau \in [\tau_0, 0]. \tag{6.82}
\]

Proof.
1. For any \(k \geq 1\), we set
\[
\begin{align*}
z^{(k)} & \equiv w^{(k+1)} - w^{(k)}, \quad M^{(k)}_z(\tau) \equiv \|z^{(k)}(\tau, \cdot)\|_{H^{2}(\{\tau, 0\})}, \\
\sigma_1^{(k, 2)}(\tau) & \equiv z^{(k)}(\tau, \tau-)-z^{(k)}(\tau, \tau+), \quad \sigma_2^{(k, 2)}(\tau) \equiv z^{(k)}(\tau, 0-)-z^{(k)}(\tau, 0+), \\
\alpha_k(\tau) & \equiv \sup_{t \in [\tau_0, \tau]} \max_{t \in [1, 2]} |\hat{\sigma}_1^{(k, 2)}(t)|, \\
\beta_k(\tau) & \equiv \sup_{t \in [\tau_0, \tau]} \left( M^{(k)}_z(t) + |z^{(k)}(t, 0-)| + z^{(k)}(t, 0+) + |z^{(k)}(t, 0-)| + |z^{(k)}(t, 0+)\right).
\end{align*}
\]
\[
\tag{6.83}
\]
Recalling Duhamel’s formula, Lemma 6.4, Lemma 6.2, (6.72), and Lemma 6.5, for all \(\tau \in [\tau_0, 0]\) we estimate
\[
\begin{align*}
M^{(k+1)}_z(\tau) & \leq \frac{3}{2} \int_{\tau_0}^{\tau} \left( \frac{4C_1 |\ln \tau|}{\delta_0 t^{2/3}} + \frac{2M_0 + 2K_2b + 1)(1 + \delta_0)}{\delta_0 t^{2/3}} \right) \beta_k(t) \cdot (\tau - t)^{-2/3} + |\ln \tau| dt \\
& + \frac{3C_2}{2\delta_0} \int_{\tau_0}^{\tau} \frac{2M_0 + 2K_2b}{\delta_0 t^{2/3}} \cdot \alpha_k(t) \cdot (\tau - t)^{-2/3} dt \\
& \leq C_3 \cdot \left( |\tau_0 - \tau|^{1/3} \cdot |\ln \tau_0 - \tau| \cdot \beta_k(\tau) + \int_{\tau_0}^{\tau} \alpha_k(t)(\tau - t)^{-2/3} dt \right)
\end{align*}
\]
\[
\tag{6.84}
\]
for some constant \(C_3\) depending only on \(M_0, b, K_2, \delta_1, \) and \(\delta_2\).

2. We now establish a bound on \(z^{(k+1)}_x(\tau, 0 \pm)\). Since
\[
|z^{(k+1)}_x(\tau, 0+)\| \leq \|z^{(k+1)}(\tau, \cdot)\|_{H^{2}(\{\tau, 0\})} \leq M^{(k+1)}_z(\tau), \tag{6.85}
\]

it suffices to have a closer look at \(z^{(k+1)}_x(\tau, 0-)\). Given \(\tau \in [\tau_0, 0]\) and \(\tau < \bar{x}_2 < \bar{x}_1 < 0\), consider the characteristics \(t \mapsto x_i(t) = x_i(t; \bar{x}_i)\) for \(i \in \{1, 2\}\). Recalling (6.75), (6.50), (6.79), and (6.70), we estimate
Moreover, by choosing \( z^{(k+1)}(\tau, x_1) \) for some constant \( C_2 \), finally, we establish a bound on \( x^{(k+1)}(\tau, t) \) for some constant \( C_4 \) depending only on \( M_0, b, K_1, \delta_1, \) and \( \delta_2 \). This implies

\[
|z^{(k+1)}(\tau, 0)| - z^{(k+1)}(\tau, 0) \leq C_4 \cdot \beta_k(\tau) \cdot |\tau - \tau_0|^{1/2}.
\]

(6.86)

3. Finally, we establish a bound on \( x_{k+1}(\tau) \) for \( \tau \in [\tau_0, 0] \). We only present here the details for \( x_{k+1}(\tau) \), since \( x_{k+1}(\tau) \) can be estimated in the same way. Given any \( \tau_0 \leq \tau_1 < \tau_2 < 0 \), denote by \( t \rightarrow x(t) = x(t; \tau_2, 0 \pm) \) the characteristics which reach the origin at time \( \tau_2 \) from the positive and negative side, respectively. Using (6.75), (6.49), (6.74), and (6.79), we estimate

\[
|z^{(k+1)}(\tau_2, 0 \pm) - z^{(k+1)}(\tau_1, 0 \pm)| \leq 2 \beta_{k+1}(\tau_1) \cdot |x_2(\tau_1)| + \int_{\tau_1}^{\tau_2} |F^{(k+1)}(t, x_2(\tau_1)) - F^{(k)}(t, x_2(\tau_1))| dt
\]

\[
\leq 2 \beta_{k+1}(\tau_1) \cdot |x_2(\tau_1)| + \frac{C_2}{\delta_0} \cdot \int_{\tau_1}^{\tau_2} (2M_0 + 2K_1b) \cdot \alpha_0(t) \cdot |x_2(\tau_1)| dt
\]

\[
+ \frac{C_2}{\delta_0} \cdot \int_{\tau_1}^{\tau_2} \beta_k(t) \cdot \left( \frac{4C_1 \sqrt{|t|}}{\delta_0} |\ln |t|| + \frac{2M_0 + 2K_1b}{\delta_0} + \frac{8C_1}{\delta_0} |\ln |t|| |\tau_2 - t|^{1/2} \right) dt
\]

\[
\leq \left( 2 \beta_{k+1}(\tau_2) \gamma_1 + C_5 \cdot \left( \beta_k(\tau_2) \cdot |\ln |x_2(\tau)| + \alpha_0(\tau_2) \cdot |\tau_2 - t|^{1/2} \right) \right) (\tau_2 - \tau_1)
\]

for some constant \( C_5 \) depending only on \( M_0, b, K_1, \delta_1, \) and \( \delta_2 \). Thus, for \( \tau \in [\tau_0, 0] \),

\[
\alpha_{k+1}(\tau) \leq 2 \beta_{k+1}(\tau) \gamma_1 + C_5 \cdot \beta_k(\tau) \cdot |\ln |t||.
\]

(6.87)

Moreover, by choosing \( \tau_1 = \tau_0 \) and \( \tau_2 = \tau \in [\tau_0, 0] \), we also get

\[
|z^{(k+1)}(\tau, 0 \pm)| \leq C_6 \cdot \left( \beta_k(\tau) \cdot |\tau - \tau_0| \cdot |\ln |\tau - \tau_0|| + \int_{\tau_0}^{\tau} \alpha_k(t) \cdot |t - \tau|^{1/2} dt \right),
\]

and (6.84)–(6.87) imply that

\[
\beta_{k+1}(\tau) \leq C_7 \cdot \left( |\tau - \tau_0|^{1/3} \cdot |\ln |\tau - \tau_0|| \cdot \beta_k(\tau) + \int_{\tau_0}^{\tau} \alpha_k(t) \cdot |t - \tau|^{-2/3} dt \right)
\]

\[
\leq C_8 \cdot |\tau - \tau_0|^{1/3} \cdot |\ln |\tau - \tau_0|| \cdot (\beta_k(\tau) + \beta_{k-1}(\tau)).
\]
In particular, for $\tau_0 < 0$ sufficiently close to 0, we get
\[
\beta_{k+1}(\tau) + \frac{1}{2} \beta_k \leq \frac{3}{4} \left( \beta_k(\tau) + \frac{1}{2} \beta_{k-1} \right),
\]
which implies
\[
\sum_{k=1}^{\infty} \sup_{\tau \in [\tau_0,0]} \|z^{(k)}(\tau, \cdot)\|_{H^2(\mathbb{R} \setminus \{t,0\})} < \sum_{k=1}^{\infty} \beta_k(\tau) < \infty.
\]

We thus conclude that $(w^{(k)}(\tau, \cdot))_{k \geq 1}$ converges uniformly for all $\tau \in [\tau_0,0]$ to a limit function $w(\tau, \cdot)$ in $H^2(\mathbb{R} \setminus \{t,0\})$, which provides the solution to the linear problem (6.22). Moreover, since $\lim_{k \to -\infty} w^{(k)}(\tau,0, \pm) = w(\tau,0, \pm)$ and $\lim_{k \to -\infty} w^{(k)}(\tau, \pm) = w(\tau, \pm)$, one has that $\lim_{k \to -\infty} \sigma_{1}^{(k)}(\tau) = \sigma_{1}(\tau)$ for all $\tau \in [0,\tau]$. Furthermore, $\lim_{k \to -\infty} w_{x}^{(k)}(\tau,0, \pm) = w_{x}(\tau,0, \pm)$ and $\lim_{k \to -\infty} w_{x}^{(k)}(\tau, \pm) = w_{x}(\tau, \pm)$ and hence Lemma 6.5 implies that $w$ satisfies (6.80)–(6.82).

We are now ready to complete the proof of our second main theorem, describing the asymptotic behavior of solutions up to the time when two shocks interact.

**Proof of Theorem 6.1.**

1. By induction, we construct a sequence of approximate solutions $(w^{(n)})_{n \geq 1}$ where each $w^{(n+1)}$ is the solution to the linear problem (6.22). Assuming that $\tau_0 \in [-\varepsilon_0,0]$ is sufficiently close to 0, we claim that
\[
\sum_{n=1}^{\infty} \|w^{(n+1)}(t, \cdot) - w^{(n)}(t, \cdot)\|_{H^2(\mathbb{R} \setminus \{t,0\})} < \infty \quad \text{for all } t \in [\tau_0,0].
\]

For a fixed $n \geq 2$, recalling that $a_n(t,x) = \frac{w^{(n)}(t,x) + \phi^{(n)}(t,x) - a^{(n)}_1(t)}{a^{(n)}_2(t) - a^{(n)}_1(t)}$, we define
\[
\begin{cases}
W^{(n)} = w^{(n)} - w^{(n-1)}, & A^{(n)}(\tau, x) = a_n(\tau, x) - a_{n-1}(\tau, x), \\
A^{(n)}_1(\tau) = W^{(n)}(\tau, \tau -) - W^{(n)}(\tau, \tau +), & A^{(n)}_2(\tau) = W^{(n)}(\tau, 0 -) - W^{(n)}(\tau, 0 +), \\
\beta^{(n)}(\tau) = \sup_{\tau \in [\tau_0,0]} \left[ \|W^{(n)}(\tau, \cdot)\|_{H^2(\mathbb{R} \setminus \{t,0\})} + |W^{(n)}(\tau, 0 -)| + |W^{(n)}(\tau, 0 +)| \right].
\end{cases}
\]

Set $Z^{(n)} = W^{(n)} + V^{(n)}$ with $V^{(n)} = \psi^{(n)} - \psi^{(n-1)}$ and $\psi^{(n)} = \phi_0(x) - \phi_0(x - t) - \phi_0(x)$. From the above definitions, by (6.22), we deduce
\[
Z^{(n+1)}_t + a_n \cdot Z^{(n+1)}_x = -\left( A^{(n)} w^{(n)} + A^{(n+1)} v^{(n+1)} \right) + G^{(n+1)} - G^{(n)}
\]
with
\[
G^{(n)}(t,x) = H \left[ \frac{w^{(n)}(t, \cdot) + \phi^{(n)}(t, \cdot)}{a^{(n)}_1(t) - a^{(n)}_2(t)} \right](x) - a_n(t,x) \cdot \left[ \phi'_0(x - t) + \phi'_0(x) \right].
\]

We split
\[
w^{(n)} = v_{1,n} + v_{2,n}, \quad v_{2,n}(t,x) = \begin{cases} w(t,0-) \cdot \eta(x), & x < 0, \\
w(t,0+) \cdot \eta(x), & 0 < x.
\end{cases}
\]

Recalling the definition of $\tilde{B}$ and $\tilde{C}$ in (6.26)–(6.27), we write
Here it is important to note that \( W_j^{(n)} = v_j^{(n)} - v_j^{(n-1)} \) satisfies

\[
\| W_j^{(n)} (t, \cdot) \|_{H^1(\mathbb{R} \setminus \{t, 0\})} \leq O(1) \left( M^{(n)}(t) + |W^{(n)}(t, 0^-)| + |W^{(n)}(t, 0^+)| \right) \\
\leq O(1) \cdot \beta^{(n)}(t),
\]

while, (6.31) implies,

\[
\| v_j^{(n)} (t, \cdot) \|_{H^1(\mathbb{R} \setminus \{t, 0\})} \leq O(1) \| w^{(n)} \|_{H^1(\mathbb{R} \setminus \{t, 0\})} \leq O(1)M_0.
\]

Recalling (6.31), (3.10), (3.20), (6.34), (3.6), (3.5), and (6.36), we get

\[
\begin{cases}
| (G^{(n+1)} - G^{(n)}) (\tau, x) | \leq \Gamma_1 \cdot \beta^{(n+1)}(\tau), & \tau < x < 0, \\
\| (G^{(n+1)} - G^{(n)}) (\tau, \cdot) \|_{H^1(\mathbb{R} \setminus [-\delta, \delta] \cup [\tau-\delta, \tau+\delta])} \leq \Gamma_1 \cdot \frac{\beta^{(n+1)}(\tau)}{\delta^{1/2}},
\end{cases}
\]

for some positive constant \( \Gamma_1 \). Furthermore, we have for all \( x \left[ -\frac{1}{2}, \frac{1}{2} \right] \setminus \{\tau, 0\} \) that

\[
\begin{cases}
| A^{(n)} w_x^{(n)} (\tau, x) | \leq \Gamma_2 \beta^{(n)}(\tau), & |A^{(n)} w_x^{(n)} (\tau, x)| \leq \Gamma_2 \beta^{(n)}(\tau) \cdot (|x|^{-1/2} + |x - \tau|^{-1/2}), \\
\| A^{(n)} w_x^{(n)} (\tau, \cdot) \|_{H^1(\mathbb{R} \setminus \{\tau, 0\})} \leq \Gamma_2 \beta^{(n)}(\tau), & \| A^{(n)} w_x^{(n)} (\tau, \cdot) \|_{H^1(\mathbb{R} \setminus [-\delta, \delta] \cup [\tau-\delta, \tau+\delta])} \leq \frac{\Gamma_2 \beta^{(n)}(\tau)}{\delta^{1/2}},
\end{cases}
\]

for some constant \( \Gamma_2 > 0 \), dependent on \( M_0, b, \delta_1, \) and \( \delta_2 \). Hence, if \( \tau_0 < 0 \) is sufficiently close to 0, we have, using Duhamel’s formula and (6.71), for all \( \tau \in [\tau_0, 0[ \) that

\[
\| Z^{(n+1)} (\tau, \cdot) \|_{H^1(\mathbb{R} \setminus \{\tau, 0\})} \leq \frac{3}{2} \int_{\tau_0}^{\tau} \left\| \left[ C^{(n+1)} - G^{(n)} - A^{(n)} w_x^{(n)} - A^{(n+1)} w_x^{(n+1)} \right] (t, \cdot) \right\|_{H^1(\mathbb{R} \setminus \{t\})} dt \\
\leq \frac{3}{2} \left( \Gamma_1 + \Gamma_2 \right) \cdot \int_{\tau_0}^{\tau} \beta^{(n)}(t) + \beta^{(n+1)}(t) \cdot \gamma_0^{-1/2} (\tau - t)^{-1/2} dt.
\]

Thus, there exists a constant \( \Gamma_3 > 0 \) dependent on \( M_0, b, \delta_1, \) and \( \delta_2 \) such that

\[
\| Z^{(n+1)} (\tau, \cdot) \|_{H^1(\mathbb{R} \setminus \{\tau, 0\})} \leq \Gamma_3 \cdot \left( \beta^{(n)}(\tau) \cdot |\tau_0 - \tau| + \beta^{(n+1)}(\tau) \cdot |\tau_0 - \tau|^{1/2} \right).
\]

2. We establish a bound on \( |Z^{(n+1)}(\tau, 0\pm)| \). Given any \( \tau_0 \leq \tau \leq 0 \), let \( t \mapsto x_2(t) = x(t; \tau, 0^-) \) be the characteristic, which reaches the origin at time \( \tau \) from the negative side. Since

\[
Z^{(n+1)}(\tau_0, x) \equiv 0, \quad |Z^{(n+1)}(\tau, 0\pm)| \leq \| Z^{(n+1)} (\tau, \cdot) \|_{H^1(\mathbb{R} \setminus \{\tau, 0\})},
\]

we have
\[ |Z^{(n+1)}(\tau,0-)| \leq \int_{\tau_0}^{\tau} \left| (-A^{(n)}w^{(n)} + A^{(n+1)}v^{(n+1)} + G^{(n+1)} - G^{(n)})(t,x_2(t)) \right| dt \]

\[ \leq (\Gamma_1 + \Gamma_2) \cdot \int_{\tau_0}^{\tau} \beta^{(n)}(t) + \beta^{(n+1)}(t) \cdot \left( 1 + 2t_0^{-1/2}(\tau - t)^{-1/2} \right) dt \]

\[ \leq \Gamma_4 \cdot \left( \beta^{(n)}(\tau) \cdot |\tau - \tau_0| + \beta^{(n+1)}(\tau) \cdot |\tau - \tau_0|^{1/2} \right), \]  

where we used (6.74) and \( \Gamma_4 \) denotes a positive constant dependent on \( M_0, b, \delta_1, \) and \( \delta_2 \). Combining (6.92) - (6.94), we end up with

\[ \|Z^{(n+1)}(\tau,\cdot)\|_{H^1(\mathbb{R}\setminus\{\tau,0\})} + \|Z^{(n+1)}(\tau,0-)\| + |Z^{(n+1)}(\tau,0+)| \]

\[ \leq \Gamma_5 \cdot \left( \beta^{(n)}(\tau) \cdot |\tau - \tau_0| + \beta^{(n+1)}(\tau) \cdot |\tau - \tau_0|^{1/2} \right), \]

where \( \Gamma_5 > 0 \) denotes a constant dependent on \( M_0, b, \delta_1, \) and \( \delta_2 \).

3. From (6.34), it holds that \( W^{(n+1)}(\tau,\tau\pm) = Z^{(n+1)}(\tau,\tau\pm), W^{(n+1)}(\tau,0\pm) = Z^{(n+1)}(\tau,0\pm), \) and

\[ \|V^{(n+1)}(\tau,\cdot)\|_{H^1(\mathbb{R}\setminus\{\tau,0\})} \]

\[ \leq \Gamma_6 \cdot \left( |W^{(n+1)}(\tau,\tau-) + |W^{(n+1)}(\tau,\tau+) + |W^{(n+1)}(\tau,0-) + |W^{(n+1)}(\tau,0+)\right| \]

\[ = \Gamma_6 \cdot \left( |Z^{(n+1)}(\tau,\tau-) + |Z^{(n+1)}(\tau,\tau+) + |Z^{(n+1)}(\tau,0-) + |Z^{(n+1)}(\tau,0+)\right| \]

\[ \leq 3\Gamma_6 \cdot \left( \|Z^{(n+1)}(\tau,\cdot)\|_{H^1(\mathbb{R}\setminus\{\tau,0\})} + |Z^{(n+1)}(\tau,0-) + |Z^{(n+1)}(\tau,0+)\right| \]

for some positive constant \( \Gamma_6 \) on \( M_0, b, \delta_1, \) and \( \delta_2 \). Thus, we end up with

\[ \beta^{(n+1)}(\tau) \leq (1 + 3\Gamma_6) \left( \|Z^{(n+1)}(\tau,\cdot)\|_{H^1(\mathbb{R}\setminus\{\tau,0\})} + |Z^{(n+1)}(\tau,0-) + |Z^{(n+1)}(\tau,0+)\right| \]

\[ \leq \Gamma_7 \left( \beta^{(n)}(\tau) \cdot |\tau - \tau_0| + \beta^{(n+1)}(\tau) \cdot |\tau - \tau_0|^{1/2} \right). \]

Provided that \( \tau_0 < 0 \) is sufficiently close to 0, we obtain that

\[ \beta^{(n+1)}(\tau) \leq \beta^{(n)}(\tau)/2 \quad \text{for all} \ \tau \in [\tau_0,0[. \]

Thus, (6.88) holds for all \( \tau \in [\tau_0,0], \) and the sequence of approximations \( w^{(n)}(\tau,\cdot) \) is Cauchy in the space \( H^1(\mathbb{R}\setminus\{\tau,0\}), \) and hence it converges to a unique limit \( w(\tau,\cdot). \)

It remains to check that this limit function \( w \) is an entropic solution, i.e., it satisfies, cf. (6.5), (6.7), and (6.13),

\[ (w + \varphi^{(w)})(t_0,x_0) = (\bar{w} + \bar{\varphi})(x(\tau_0)) + \int_{\tau_0}^{t_0} \frac{H[w + \varphi^{(w)}](t,x(t))}{a_1(t) - a_2(t)} dt, \]

where \( t \mapsto x(t; t_0,x_0) \) denotes the characteristics curve, obtained by solving \( \dot{x} = a(t,x,w) \) with \( x(t_0) = x_0. \) This follows from slightly rewriting (2.19), which yields
\[
\begin{align*}
(W^{(n+1)} + \phi^{(n+1)})(t_0, x_0) &= \left(\tilde{w} + \tilde{\varphi}\right)(x_n(\tau_0)) + \int_{\tau_0}^{t_0} \frac{H[W^{(n+1)} + \phi^{(n+1)}](t, x_n(t))}{}
\end{align*}
\]

where \( t \mapsto x_n(t) \) denotes the characteristic curve, obtained by solving (6.61) with \( x_n(t_0) = x_0 \).

Finally, to prove uniqueness, assume that \( \tilde{w} \) and \( w \) are two entropic solutions. We define

\[
W \doteq \tilde{w} - w, \quad \beta(\tau) = \sup_{t \in [\tau_0, \tau]} \left[ \| W(t, \cdot) \|_{H^1(\mathbb{R} \setminus \{0\})} + |W(t, 0^-)| + |W(t, 0^+)| \right]
\]

The arguments used in the previous steps now yield the inequality

\[
\beta(\tau) \leq \beta(\tau)/2,
\]

and this implies \( Z(\tau) = 0 \) for all \( \tau \in [\tau_0, 0] \), completing the proof.

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