

CONTROLLABILITY TO SYSTEMS OF QUASILINEAR WAVE EQUATIONS WITH FEWER CONTROLS

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ABSTRACT. This study addresses challenges in solving exact boundary controllability problems of quasilinear wave equations with Dirichlet type boundary conditions satisfying some kind of Kalman rank conditions. Utilizing techniques such as characteristic method and a specially designed linearization iteration scheme, we developed controls that use fewer boundary controls than the classical theory.

1. INTRODUCTION

Consider the controllability for system of the quasilinear wave equations below

$$\begin{cases} U_{tt} - a^2(U, U_t, U_x) U_{xx} = 0, & (t, x) \in \mathbb{R}^+ \times [0, L], \\ t = 0 : (U, U_t) = (\varphi(x), \psi(x)), & x \in [0, L], \\ x = L : U = 0, & t \in \mathbb{R}^+, \\ x = 0 : U_t - D(U, U_t, U_x) U_x = H(t), & t \in \mathbb{R}^+, \\ t = T : (U, U_t) = (\Phi(x), \Psi(x)), & x \in [0, L], \end{cases} \quad (1.1)$$

where

$$U = (u_1, \dots, u_n)^T(t, x) \in C^2([0, T] \times [0, L]).$$

$a(U, U_t, U_x) > 0$ is smooth respect to (U, U_t, U_x) . $D(U, U_t, U_x) = (d_{ij}(U, U_t, U_x))_{i,j=1}^n$ is an $n \times n$ matrix smooth respect to (U, U_t, U_x) . Part of the components of $H(t) = (h_1(t), \dots, h_n(t))^T$ would be chosen as boundary controls. We denote $D^\pm(U, U_t, U_x) = aI_n \pm D$, which we request are invertible. We also request that

$$\begin{aligned} \|(\varphi(x), \psi(x))\|_{(C^{2,1}[0,L])^n \times (C^{1,1}[0,L])^n} &< \varepsilon, \\ \|(\Phi(x), \Psi(x))\|_{(C^{2,1}[0,L])^n \times (C^{1,1}[0,L])^n} &< \varepsilon, \end{aligned}$$

where $0 < \varepsilon < \varepsilon_0 \ll 1$. Without loss of generosity, we set $a(0, 0, 0) = 1$, or we consider the equations of $\bar{U}(t, x) = U(t, a(0, 0, 0)x)$, and $H(t) = (h_1(t), \dots, h_p(t), 0, \dots, 0)^T$. Now we try to reduce the wave equation to a hyperbolic equation system. Denote

$$\begin{aligned} \tilde{U} &= D^+(0, 0, 0)U, \\ \tilde{V}^\pm &= \partial_t \tilde{U} \mp \tilde{a}(\tilde{U}, \tilde{U}_t, \tilde{U}_x) \partial_x \tilde{U}. \end{aligned}$$

where

$$\tilde{a}(\tilde{U}, \tilde{U}_t, \tilde{U}_x) = a(D^+(0, 0, 0)^{-1}U, D^+(0, 0, 0)^{-1}U_t, D^+(0, 0, 0)^{-1}U_x).$$

Denote

$$\tilde{D}^\pm(\tilde{U}, \tilde{U}_t, \tilde{U}_x) = D^\pm(D^+(0, 0, 0)^{-1}U, D^+(0, 0, 0)^{-1}U_t, D^+(0, 0, 0)^{-1}U_x).$$

The original equations can be changed into

$$\begin{cases} \partial_t \tilde{V}^\pm \pm \tilde{a}(\tilde{U}, \tilde{U}_t, \tilde{U}_x) \partial_x \tilde{V}^\pm = \mp \partial_x \tilde{U}(\partial_t \pm \tilde{a}(\tilde{U}, \tilde{U}_t, \tilde{U}_x) \partial_x)(\tilde{a}(\tilde{U}, \tilde{U}_t, \tilde{U}_x)), \\ x = L : \tilde{V}^- = -\tilde{V}^+, \\ x = 0 : \tilde{D}^-(\tilde{U}, \tilde{U}_t, \tilde{U}_x) \tilde{D}^+(0, 0, 0)^{-1} \tilde{V}^- = -\tilde{D}^+(\tilde{U}, \tilde{U}_t, \tilde{U}_x) \tilde{D}^+(0, 0, 0)^{-1} \tilde{V}^+ + \tilde{H}(t), \end{cases} \quad (1.2)$$

where $\tilde{H}(t) = 2aH(t)$. Then the boundary condition can be written as

$$\begin{aligned} x=0 : \tilde{V}^+ &= A_0 \tilde{V}^- + \tilde{H}(t) - \left(\tilde{D}^- \left(\tilde{U}, \tilde{U}_t, \tilde{U}_x \right) - \tilde{D}^+(0, 0, 0) \right) \tilde{D}^+(0, 0, 0)^{-1} \tilde{V}^+ \\ &\quad - \left(\tilde{D}^- \left(\tilde{U}, \tilde{U}_t, \tilde{U}_x \right) - \tilde{D}^-(0, 0, 0) \right) \tilde{D}^+(0, 0, 0)^{-1} \tilde{V}^-, \end{aligned}$$

where the coupling matrix

$$A_0 = - (a(0, 0, 0)I_n - D(0, 0, 0)) (a(0, 0, 0)I_n + D(0, 0, 0))^{-1}.$$

Define the controlling matrix as

$$C = \begin{pmatrix} I_p & 0 \\ 0 & 0 \end{pmatrix},$$

and then the Kalman type condition as

$$\text{Rank} [C, A_0 C, \dots, A_0^{k-1} C] = n, \quad (1.3)$$

where k is a positive integer.

The following theorem can be obtained.

Theorem 1. Under Assumption (1.3), if $T > kL$, there exists a small $\varepsilon_0 > 0$ and a set of C^1 smooth control functions $h_i(t)$, $i = 1, \dots, p$, such that for any $\varepsilon \in (0, \varepsilon_0)$ and any $\Phi(x)$, $\varphi(x)$ which are $C^{2,1}$ smooth and satisfy the C^2 compatibility conditions and $\Psi(x)$, $\psi(x)$ which are $C^{1,1}$ smooth and satisfy the C^1 compatibility conditions, there exists a C^2 smooth solution $U(t, x)$ to the control problem (1.1).

The proof of Theorem 1 requires the following iterative scheme. Taking $U^{(0)} \equiv 0$, consider the following linearized controllability problem for $m \geq 0$:

$$\left\{ \begin{array}{l} \partial_t V^{\pm(m+1)} \pm a^{(m)} \partial_x V^{\pm(m+1)} = \mp \partial_x U^{(m)} (\partial_t \pm a^{(m)} \partial_x) (a^{(m)}) , \\ x = L : V^{-(m+1)} = -V^{+(m+1)}, \quad t \in \mathbb{R}^+, \\ x = 0 : V^{-(m+1)} = A_0 V^{+(m+1)} + \tilde{H}^{(m+1)}(t) \\ \quad + \left(\tilde{D}^+ \left(U^{(m)}, U_t^{(m)}, U_x^{(m)} \right) - \tilde{D}^+(0, 0, 0) \right) \tilde{D}^+(0, 0, 0)^{-1} V^{-(m)} \\ \quad - \left(\tilde{D}^- \left(U^{(m)}, U_t^{(m)}, U_x^{(m)} \right) - \tilde{D}^-(0, 0, 0) \right) \tilde{D}^-(0, 0, 0)^{-1} V^{+(m)}. \\ t = 0 : \left(U^{(m+1)}, U_t^{(m+1)} \right) = (\varphi(x), \psi(x)), \\ t = T : \left(U^{(m+1)}, U_t^{(m+1)} \right) = (\Phi(x), \Psi(x)), \end{array} \right. \quad (1.4)$$

where

$$a^{(m)} = a \left(U^{(m)}, U_t^{(m)}, U_x^{(m)} \right).$$

$U^{(m+1)}$ for each step can be obtained using the Dirichlet boundary condition as

$$U^{(m+1)}(t, x) = - \int_x^L \partial_x U^{(m+1)} dx,$$

where

$$\partial_x U^{(m+1)} = \frac{V^{-(m+1)} - V^{+(m+1)}}{2a \left(U^{(m)}, U_t^{(m)}, U_x^{(m)} \right)}.$$

Proposition 1.1. One can get uniform bounds

$$\|U^{(m)}\|_{C^{2,1}} \leq C_P \varepsilon, \quad (1.5)$$

$$\|H^{(m)}\|_{C^{1,1}} \leq C_P \varepsilon, \quad (1.6)$$

as well as Cauchy sequence

$$\|U^{(m)} - U^{(m-1)}\|_{C^2} \leq C_P \varepsilon \alpha^{m-1}, \quad (1.7)$$

where α is a constant satisfying $0 < \alpha < 1$ and C_P is a large constant. The sequence $\{H^{(m)}\}_{m=1}^\infty$ is also a Cauchy sequence in C^1 space, i.e.

$$\left\| H^{(m)} - H^{(m-1)} \right\|_{C^1} \leq C_P \varepsilon \alpha^{m-1}. \quad (1.8)$$

Theorem 1 follows after obtaining Proposition 1.1. In fact, The sequence $\{U^{(m)}\}_{m=1}^\infty$ is a Cauchy sequence in C^2 space, and thus converges to some C^2 function U uniformly. Therefore, U is C^2 smooth and satisfies the control condition, where

2. LINEAR CONTROLLABILITY PROBLEM

We need to introduce a lemma about the linear equation. Consider the following linear equation system

$$\begin{cases} \partial_t u_i - a(t, x) \partial_x u_i = f_i^{(1)}(t, x) (\partial_t - a(t, x) \partial_x) f_i^{(2)}(t, x), & i = 1, \dots, r, \\ \partial_t u_i + a(t, x) \partial_x u_i = f_i^{(1)}(t, x) (\partial_t + a(t, x) \partial_x) f_i^{(2)}(t, x), & i = r+1, \dots, r+s, \end{cases} \quad (2.1)$$

where $r+s = n$ and $a(t, x)$ is a $C^{1,1}$ function satisfying that $\|a(t, x) - 1\|_{C^{1,1}} \leq \varepsilon_0$. Denote $\tilde{a} = a - 1$ and $t_0 = T - kL$. ε_0 is a constant small enough. $f_i^{(\kappa)}(t, x)$, $i = 1, \dots, r+s$, $\kappa = 1, 2$ are $C^{1,1}$ functions. The boundary conditions are given as follows:

$$\begin{cases} x = 0 : u_i = \sum_{j=1}^r a_{ij} u_j + g_i(t) + h_i(t), & i = r+1, \dots, n, \\ x = L : u_i = \sum_{j=r+1}^n a_{ij} u_j + g_i(t) + h_i(t), & i = 1, \dots, r, \end{cases} \quad (2.2)$$

where $g_i(t)$, $i = 1, \dots, n$, are $C^{1,1}$ function, $h_i(t)$, $i = 1, \dots, n$, are $C^{1,1}$ controlling function. The matrix $A = (a_{ij})$, $i = 1, \dots, n$, $j = 1, \dots, n$, is a matrix. $u(t, x)$ satisfies

$$u(0, x) = \varphi(x). \quad (2.3)$$

The matrix B is defined as follows:

$$B = \begin{pmatrix} I_{r_1} & & & \\ & O_{r_2} & & \\ & & I_{s_1} & \\ & & & O_{s_2} \end{pmatrix},$$

where $r_1 + r_2 = r$, $s_1 + s_2 = s$, $r+s = n$. The Kalman rank condition is given as follows:

$$\text{Rank} [B, AB, \dots, A^{k-1}B] = n, \quad (2.4)$$

where k is a positive integer. The following lemma is the main result of this section.

Lemma 2.1. *Under the conditions of (2.4), if $T > kL$, then there exists a set of $C^{1,1}$ smooth control functions $h_i(t)$, $i = 1, \dots, r_1, r+1, \dots, r+s_1$, such that for any $C^{1,1}$ smooth functions $g_i(t)$, $f_i^\kappa(t, x)$, $i = 1, \dots, n$, $\kappa = 1, 2$ and any $C^{1,1}$ smooth functions $\varphi(x)$, $\psi(x)$, which satisfy the C^1 compatibility conditions, there exists a $C^{1,1}$ smooth solution $u(t, x)$ to the control problem (2.1)-(2.3) satisfying*

$$u(T, x) = \psi(x). \quad (2.5)$$

Proof. Without loss of generality, we can assume that k is odd, $T - kL < \frac{L}{4}$ and $\varphi(x) = 0$, or take any set of $\tilde{h}_i(t)$ that satisfies the compatibility conditions at $(0, 0)$ and $(0, L)$ and consider the equations of $\tilde{u}(t, x)$ satisfying $\tilde{u}(0, x) = \varphi(x)$ below:

$$\begin{cases} \partial_t \tilde{u}_i - a(t, x) \partial_x \tilde{u}_i = \chi(t) f_i^{(1)}(t, x) (\partial_t - a(t, x) \partial_x) f_i^{(2)}(t, x), & i = 1, \dots, r, \\ \partial_t \tilde{u}_i + a(t, x) \partial_x \tilde{u}_i = \chi(t) f_i^{(1)}(t, x) (\partial_t + a(t, x) \partial_x) f_i^{(2)}(t, x), & i = r+1, \dots, r+s, \end{cases} \quad (2.6)$$

where $\chi(t)$ is a smooth function that satisfies $\chi(t) = 1$ for $t \in [0, \frac{L}{2}]$ and $\chi(t) = 0$ for $t \in [T - \frac{L}{2}, T]$. The boundary conditions are given as follows:

$$\begin{cases} x = 0 : \tilde{u}_i = \sum_{j=1}^r a_{ij} \tilde{u}_j + \chi(t) g_i(t) + \tilde{h}_i(t), & i = r+1, \dots, r+s, \\ x = L : \tilde{u}_i = \sum_{j=r+1}^n a_{ij} \tilde{u}_j + \chi(t) g_i(t) + \tilde{h}_i(t), & i = 1, \dots, r. \end{cases} \quad (2.7)$$

Then we can get that $\tilde{u}(T, x)$ satisfies the C^1 compatibility conditions at $(T, 0)$ and (T, L) and consider the following controllability problem:

$$\begin{cases} \partial_t u_i - a(t, x) \partial_x u_i = (1 - \chi(t)) f_i^{(1)}(t, x) (\partial_t - a(t, x) \partial_x) f_i^{(2)}(t, x), & i = 1, \dots, r, \\ \partial_t u_i + a(t, x) \partial_x u_i = (1 - \chi(t)) f_i^{(1)}(t, x) (\partial_t + a(t, x) \partial_x) f_i^{(2)}(t, x), & i = r+1, \dots, r+s, \end{cases} \quad (2.8)$$

where the boundary conditions are given as follows:

$$\begin{cases} x = 0 : u_i = \sum_{j=1}^r a_{ij} u_j + (1 - \chi(t)) g_i(t) + h_i(t), & i = r+1, \dots, r+s, \\ x = L : u_i = \sum_{j=r+1}^n a_{ij} u_j + (1 - \chi(t)) g_i(t) + h_i(t), & i = 1, \dots, r. \end{cases} \quad (2.9)$$

The initial and final conditions are given as follows:

$$u(0, x) = 0, \quad u(T, x) = \psi(x) - \tilde{u}(T, x). \quad (2.10)$$

Finally, the two sets of control functions and solutions obtained can be added separately.

In the following we first study the characteristic lines of equations. Let

$$b(t, x) = \frac{1}{a(t, x)}.$$

The characteristic lines of the system (2.1) are given as follows:

$$\begin{cases} \frac{d\tilde{t}_p}{dx} = -b(\tilde{t}_p, x), \\ \tilde{t}_p(0; x_0) = t_{p-1}(0; x_0), \quad p = 2, \dots, k+1, \\ \tilde{t}_1(x_0; x_0) = T, \end{cases} \quad (2.11)$$

$$\begin{cases} \frac{dt_p}{dx} = b(t_p, x), \\ t_p(L; x_0) = \tilde{t}_{p-1}(L; x_0), \quad p = 2, \dots, k+1, \\ t_1(x_0; x_0) = T, \end{cases} \quad (2.12)$$

thereby obtaining the following equations:

$$\begin{aligned} t_1(x; x_0) &= T + \int_{x_0}^x b(t_1(s; x_0), s) ds, \\ t_p(x; x_0) &= t_{p-1}(L; x_0) + \int_L^x b(t_p(s; x_0), s) ds, \quad p = 2, \dots, k+1, \\ \partial_{x_0} t_1(x; x_0) &= -b(T, x_0) + \int_{x_0}^x \partial_t b(t_1(s; x_0), s) \partial_{x_0} t_1(s; x_0) ds, \\ \partial_{x_0} t_p(x; x_0) &= \partial_{x_0} t_{p-1}(L; x_0) + \int_L^x \partial_t b(t_p(s; x_0), s) \partial_{x_0} t_p(s; x_0) ds, \quad p = 2, \dots, k+1. \end{aligned} \quad (2.13)$$

Denote $z_p(x; x_0) = \partial_{x_0} t_p(x; x_0)$, which conduces that

$$\frac{d}{dx} z_p(x; x_0) = \partial_t b_p(t(x; x_0), x) z_p(x; x_0).$$

Then we can get the following equations:

$$\begin{aligned} z_1(x; x_0) &= -b(T, x_0) \exp \left(\int_{x_0}^x \partial_t b(t_1(s; x_0), s) ds \right), \\ z_p(x; x_0) &= \partial_{x_0} t_{p-1}(L; x_0) \exp \left(\int_L^x \partial_t b(t_p(s; x_0), s) ds \right). \end{aligned} \quad (2.14)$$

Similarly one can obtain that

$$\begin{aligned}\tilde{t}_1(x; x_0) &= T - \int_{x_0}^x b(\tilde{t}_1(s; x_0), s) ds, \\ \tilde{t}_p(x; x_0) &= t_{p-1}(0; x_0) - \int_0^x b(\tilde{t}_p(s; x_0), s) ds, \quad p = 2, \dots, k+1, \\ \tilde{z}_1(x; x_0) &= b(T, x_0) \exp\left(-\int_{x_0}^x \partial_t b(\tilde{t}_1(s; x_0), s) ds\right), \\ \tilde{z}_p(x; x_0) &= \partial_{x_0} t_{p-1}(0; x_0) \exp\left(\int_0^x \partial_t b(\tilde{t}_p(s; x_0), s) ds\right), \quad p = 2, \dots, k+1.\end{aligned}$$

Therefore

$$\begin{cases} t_1(x; 0) = T, \\ t_{2m+1}(x; 0) = t_{2m}(x; 0), \\ t_{2m}(x; L) = t_{2m-1}(x; L), \end{cases} \quad (2.15)$$

$$\begin{cases} \tilde{t}_1(x; L) = T, \\ \tilde{t}_{2m+1}(x; L) = \tilde{t}_{2m}(x; L), \\ \tilde{t}_{2m}(x; 0) = \tilde{t}_{2m-1}(x; 0), \end{cases} \quad (2.16)$$

and

$$\begin{cases} \partial_{x_0} t_1(x; 0) = -b(T, 0), \\ \partial_{x_0} t_{2m+1}(x; 0) = -\partial_{x_0} t_{2m}(x; 0), \\ \partial_{x_0} t_{2m}(x; L) = -\partial_{x_0} t_{2m-1}(x; L), \end{cases} \quad (2.17)$$

$$\begin{cases} \partial_{x_0} \tilde{t}_1(x; L) = b(T, L), \\ \partial_{x_0} \tilde{t}_{2m+1}(x; L) = -\partial_{x_0} \tilde{t}_{2m}(x; L), \\ \partial_{x_0} \tilde{t}_{2m}(x; 0) = -\partial_{x_0} \tilde{t}_{2m-1}(x; 0). \end{cases} \quad (2.18)$$

The following defines a set of vector functions:

$$H_p(x) = (H^-(\tilde{t}_p(L; x)), H^+(t_p(0; x)))^T, \quad p = 1, \dots, k+1,$$

where $H^-(t)$ is an r -dimensional vector function and $H^+(t)$ is an s -dimensional vector function defined as follows:

$$\begin{aligned}H^-(t) &= (h_1(t), \dots, h_{r_1}(t), 0, \dots, 0), \\ H^+(t) &= (h_{r+1}(t), \dots, h_{r+s_1}(t), 0, \dots, 0).\end{aligned}$$

We require that $\tilde{t}_{k+1}(x; x_0) = 0$ if there exists such $\tilde{x} \in [0, L]$ such that $\tilde{x} \leq x$ and $\tilde{t}_{k+1}(\tilde{x}; x_0) = 0$, and $t_{k+1}(x; x_0) = 0$ if there exists such $\hat{x} \in [0, L]$ such that $\hat{x} \geq x$ and $t_{k+1}(\hat{x}; x_0) = 0$. Denote

$$\begin{aligned}u(t, x) &= (u^-(t, x), u^+(t, x))^T, \\ H(t) &= (H^-(t), H^+(t))^T,\end{aligned}$$

where

$$\begin{aligned}u^-(t, x) &= (u_1(t, x), \dots, u_r(t, x)), \\ u^+(t, x) &= (u_{r+1}(t, x), \dots, u_{r+s}(t, x)).\end{aligned}$$

Define

$$G_p(x) = (G^-(\tilde{t}_p(L; x)), G^+(t_p(0; x)))^T,$$

where

$$\begin{aligned}G^-(t) &= (g_1(t), \dots, g_r(t)), \\ G^+(t) &= (g_{r+1}(t), \dots, g_{r+s}(t)).\end{aligned}$$

Define

$$\begin{aligned}F_1(x) &= \left(\int_x^L F^-(\tilde{t}_1(s; x), s) ds, \int_0^x F^+(t_1(s; x), s) ds \right)^T, \\ F_p(x) &= \left(\int_0^L F^-(\tilde{t}_p(s; x), s) ds, \int_0^L F^+(t_p(s; x), s) ds \right)^T, \quad p = 2, \dots, k+1,\end{aligned}$$

where

$$\begin{aligned} F^-(t, x) &= \left(f_1^{(1)}(t, x)(b(t, x)\partial_t - \partial_x)f_1^{(2)}(t, x), \dots, f_r^{(1)}(t, x)(b(t, x)\partial_t - \partial_x)f_r^{(2)}(t, x) \right), \\ F^+(t, x) &= \left(f_{r+1}^{(1)}(t, x)(b(t, x)\partial_t - \partial_x)f_1^{(2)}(t, x), \dots, f_{r+s}^{(1)}(t, x)(b(t, x)\partial_t - \partial_x)f_{r+s}^{(2)}(t, x) \right). \end{aligned}$$

If a solution $u(t, x)$ satisfying the requirement exists, for any $x \in [0, L]$, we can get the following equations with characteristic lines method:

$$\begin{aligned} \psi(x) &= u(T, x) \\ &= (u^-(\tilde{t}_1(L; x), L), u^+(t_1(0; x), 0))^T + F_1(x) \\ &= A(u^-(t_1(0; x), 0), u^+(\tilde{t}_2(L; x), L))^T + BH_1(x) + G_1(x) + F_1(x) \\ &= A(u^-(t_2, L), u^+(\tilde{t}_2, 0))^T + AF_2(x) + BH_1(x) + G_1(x) + F_1(x) \\ &\quad \dots \\ &= A^k B(H_{k+1}(x) + G_{k+1}(x) + F_{k+1}(x)) + \dots + B(H_1(x) + G_1(x) + F_1(x)), \quad x \in [0, L]. \end{aligned} \tag{2.19}$$

Using this equation, we first determine the value and derivative of h_i at $t_p(0; 0)$, $t_p(0; L)$, $t_p(L; 0)$ and $t_p(L; L)$, ($i = 1, \dots, n$; $p = 1, \dots, k+1$). Consider the vector $\tilde{G}(x) = \sum_{l=0}^k A^l G_{l+1}(x)$.

$$\begin{aligned} \tilde{G}^-(L) &= G_1^-(L) + A_1 G_2^+(L) + A_1 A_2 G_3^-(L) + \dots + A_1 A_2 \dots A_1 G_{k+1}^+(L), \\ \tilde{G}^+(L) &= G_1^+(L) + A_2 G_2^-(L) + A_2 A_1 G_3^+(L) + \dots + A_2 A_1 \dots A_2 G_{k+1}^-(L). \end{aligned}$$

Recognizing (2.15)-(2.16) and $T - kL < \frac{L}{4}$, we can get

$$\begin{aligned} G_{k+1}^-(L) &= 0, \\ G_m^+(L) &= G_{m+1}^+(L), \quad m \text{ is odd of } 1, \dots, k, \\ G_m^+(L) &= G_{m+1}^-(L), \quad m \text{ is even of } 1, \dots, k. \end{aligned}$$

Therefore,

$$\begin{aligned} \tilde{G}^+(L) &= G_1^+(L) + A_2 G_2^-(L) + A_2 A_1 G_3^+(L) + \dots + A_2 A_1 \dots A_1 G_k^+(L) \\ &= G_2^+(L) + A_2 G_3^-(L) + A_2 A_1 G_4^+(L) + \dots + A_2 A_1 \dots A_1 G_{k+1}^+(L), \end{aligned} \tag{2.20}$$

and thereby we can get the following equations:

$$\tilde{G}^-(L) = G_1^-(L) + A_1 \tilde{G}^+(L).$$

Similarly,

$$\tilde{G}^+(0) = G_1^+(0) + A_2 \tilde{G}^-(0).$$

Namely,

$$\begin{pmatrix} \tilde{G}^-(L) \\ \tilde{G}^+(0) \end{pmatrix} = \begin{pmatrix} A_1 \\ A_2 \end{pmatrix} \begin{pmatrix} \tilde{G}^-(0) \\ \tilde{G}^+(L) \end{pmatrix} + \begin{pmatrix} g^-(T) \\ g^+(T) \end{pmatrix}. \tag{2.21}$$

Now consider the vector $\tilde{F}(x) = \sum_{l=0}^k A^l F_{l+1}(x)$.

$$\begin{aligned} \tilde{F}^-(L) &= F_1^-(L) + A_1 F_2^+(L) + A_1 A_2 F_3^-(L) + \dots + A_1 A_2 \dots A_1 F_{k+1}^+(L), \\ \tilde{F}^+(L) &= F_1^+(L) + A_2 F_2^-(L) + A_2 A_1 F_3^+(L) + \dots + A_2 A_1 \dots A_2 F_{k+1}^-(L). \end{aligned}$$

From the defination of $\chi(t)$, we can assume that $f_i^{(\kappa)}(t, x) = 0$, $t < \frac{L}{2}$, $\kappa = 1, 2$, $i = 1, \dots, n$. Recognizing (2.15)-(2.16) and $T - kL < \frac{L}{4}$, we can get

$$\begin{aligned} F_1^-(L) &= 0, \\ F_{k+1}^-(L) &= 0, \\ F_m^+(L) &= F_{m+1}^+(L), \quad m \text{ is odd of } 1, \dots, k, \\ F_m^+(L) &= F_{m+1}^-(L), \quad m \text{ is even of } 1, \dots, k. \end{aligned}$$

Therefore,

$$\begin{aligned}\tilde{F}^+(L) &= F_1^+(L) + A_2 F_2^-(L) + A_2 A_1 F_3^+(L) + \cdots + A_2 A_1 \cdots A_1 F_k^+(L) \\ &= F_2^+(L) + A_2 F_3^-(L) + A_2 A_1 F_4^+(L) + \cdots + A_2 A_1 \cdots A_1 F_{k+1}^+(L),\end{aligned}\quad (2.22)$$

and thereby we can get the following equations:

$$\tilde{F}^-(L) = A_1 \tilde{F}^+(L).$$

Similarly,

$$\tilde{F}^+(0) = A_2 \tilde{F}^-(0).$$

Namely,

$$\begin{pmatrix} \tilde{F}^-(L) \\ \tilde{F}^+(0) \end{pmatrix} = \begin{pmatrix} A_1 \\ A_2 \end{pmatrix} \begin{pmatrix} \tilde{F}^-(0) \\ \tilde{F}^+(L) \end{pmatrix}. \quad (2.23)$$

The C^0 compatibility condition of $\psi(x)$ is

$$\psi_i(0) = \sum_{j=1}^r a_{ij} \psi_j(0) + g_i(T), \quad i = r+s_1+1, \dots, r+s, \quad (2.24)$$

$$\psi_i(L) = \sum_{j=r+1}^n a_{ij} \psi_j(L) + g_i(T), \quad i = r_1+1, \dots, r. \quad (2.25)$$

So $\psi - \tilde{G} - \tilde{F}$ satisfies the conditions of Lemma A.1. Therefore, the following equations have a solution:

$$\psi(0) = A^k (H_{k+1}(0) + G_{k+1}(0) + F_{k+1}(0)) + \cdots + (H_1(0) + G_1(0) + F_1(0)), \quad (2.26)$$

$$\psi(L) = A^k (H_{k+1}(L) + G_{k+1}(L) + F_{k+1}(L)) + \cdots + (H_1(L) + G_1(L) + F_1(L)), \quad (2.27)$$

to determine the values of h_i at $t_p(0; 0), t_p(0; L), t_p(L; 0), t_p(L; L)$, ($i = 1, \dots, n; p = 1, \dots, k+1$). Derivation of (2.19) with respect to x gives the following equations:

$$\psi'(x) = A^k B(H'_{k+1}(x) + G'_{k+1}(x) + F'_{k+1}(x)) + \cdots + B(H'_1(x) + G'_1(x) + F'_1(x)), \quad x \in [0, L], \quad (2.28)$$

where

$$H'_p(x) = \left(\frac{dH^-}{dt}(\tilde{t}_p(L; x)) \frac{\partial \tilde{t}_p(L; x)}{\partial x}, \frac{dH^+}{dt}(t_p(0; x)) \frac{\partial t_p(0; x)}{\partial x} \right)^T,$$

$$G'_p(x) = \left(\frac{dG^-}{dt}(\tilde{t}_p(L; x)) \frac{\partial \tilde{t}_p(L; x)}{\partial x}, \frac{dG^+}{dt}(t_p(0; x)) \frac{\partial t_p(0; x)}{\partial x} \right)^T,$$

$$\begin{aligned}F'_1(x) &= \left(-f^{(1)-}(b\partial_t - \partial_x) f^{(2)-}(T, x) + \int_x^L \frac{\partial f^{(1)-}}{\partial t} (b\partial_t - \partial_x) f^{(2)-}(\tilde{t}_1(s, x), s) \frac{\partial \tilde{t}_1}{\partial x}(s; x) ds \right. \\ &\quad \left. - \int_x^L \frac{\partial f^{(2)-}}{\partial t} (b\partial_t - \partial_x) f^{(1)-}(\tilde{t}_1(s, x), s) \frac{\partial \tilde{t}_1}{\partial x}(s; x) ds + f^{(1)-} \frac{\partial f^{(2)-}}{\partial t}(\tilde{t}_1(s; x), s) \frac{\partial \tilde{t}_1}{\partial x}(s; x) \right|_x^L, \\ f^{(1)+}(b\partial_t - \partial_x) f^{(2)+}(T, x) &+ \int_0^x \frac{\partial f^{(1)+}}{\partial t} (b\partial_t - \partial_x) f^{(2)+}(t_1(s, x), s) \frac{\partial t_1}{\partial x}(s; x) ds \\ &- \int_0^x \frac{\partial f^{(2)+}}{\partial t} (b\partial_t - \partial_x) f^{(1)+}(t_1(s, x), s) \frac{\partial t_1}{\partial x}(s; x) ds + f^{(1)+} \frac{\partial f^{(2)+}}{\partial t}(t_1(s; x), s) \frac{\partial t_1}{\partial x}(s; x) \Big|_0^x \right)^T,\end{aligned}$$

$$\begin{aligned}
F'_p(x) = & \left(f^{(1)-} \frac{\partial f^{(2)-}}{\partial t} (\tilde{t}_p(s; x), s) \frac{\partial \tilde{t}_p}{\partial x}(s; x) \Big|_0^L + \int_0^L \frac{\partial f^{(1)-}}{\partial t} (b\partial_t - \partial_x) f^{(2)-} (\tilde{t}_p(s, x), s) \frac{\partial \tilde{t}_p}{\partial x}(s; x) ds \right. \\
& - \int_0^L \frac{\partial f^{(2)-}}{\partial t} (b\partial_t - \partial_x) f^{(1)-} (\tilde{t}_p(s, x), s) \frac{\partial \tilde{t}_p}{\partial x}(s; x) ds, \\
& f^{(1)+} \frac{\partial f^{(2)+}}{\partial t} (t_p(s; x), s) \frac{\partial t_p}{\partial x}(s; x) \Big|_0^L + \int_0^L \frac{\partial f^{(1)+}}{\partial t} (b\partial_t - \partial_x) f^{(2)+} (t_p(s, x), s) \frac{\partial t_p}{\partial x}(s; x) ds \\
& \left. - \int_0^L \frac{\partial f^{(2)+}}{\partial t} (b\partial_t - \partial_x) f^{(1)+} (t_p(s, x), s) \frac{\partial t_p}{\partial x}(s; x) ds \right)^T.
\end{aligned}$$

Consider the vector $\tilde{G}'(x) = \sum_{l=0}^k A^l G'_{l+1}(x)$ and $\tilde{F}'(x) = \sum_{l=0}^k A^l F'_{l+1}(x)$. Similar to the previous case using (2.15)-(2.18), we can get the following equations:

$$\begin{aligned}
\tilde{G}'^{-'}(L) &= b(T, L) g'^{-'}(T) - A_1 \tilde{G}'^{+'}(L), \\
\tilde{G}'^{+'}(0) &= -b(T, L) g'^{+'}(T) - A_2 \tilde{G}'^{-'}(0), \\
\tilde{F}'^{-'}(L) + f^{(1)-'}(T, L) \partial_s f^{(2)-'}(T, L) &= A_1 \left(-\tilde{F}'^{+'}(L) + f^{(1)+'}(T, L) \partial_s f^{(2)+'}(T, L) \right), \\
-\tilde{F}'^{+'}(0) + f^{(1)+'}(T, 0) \partial_s f^{(2)+'}(T, 0) &= A_2 \left(\tilde{F}'_{-}(L) + f^{(1)-'}(T, 0) \partial_s f^{(2)-'}(T, 0) \right).
\end{aligned}$$

Combined with the C^1 compatibility condition satisfied by $\psi(x)$:

$$\begin{aligned}
&a(T, L) \psi'^{-'}(L) + f^{(1)-}(\partial_t - a(T, L) \partial_x) f^{(2)-}(T, L) \\
&= A_2 (-a(T, L) \psi'^{+'}(L) + f^{(1)+}(\partial_t + a(T, L) \partial_x) f^{(2)+}(T, L)) \\
&\quad + g'^{-'}(T) + h'^{-'}(T). \\
&-a(T, 0) \psi'^{+'}(0) + f^{(1)+}(\partial_t + a(T, 0) \partial_x) f^{(2)+}(T, 0) \\
&= A_2 (a(T, 0) \psi'^{-'}(0) + f^{(1)-}(\partial_t - a(T, 0) \partial_x) f^{(2)-}(T, 0)) \\
&\quad + g'^{+'}(T) + h'^{+'}(T).
\end{aligned}$$

we know that the vector $(\psi'^{-'} - \tilde{G}'^{-'} - \tilde{F}'^{-'}, -\psi'^{+'} + \tilde{G}'^{+'} + \tilde{F}'^{+'})^T$ stastisfies the conditions of Lemma A.1. Therefore, the following equations have a solution:

$$\psi'(0) = A^k B(H'_{k+1}(0) + G'_{k+1}(0) + F'_{k+1}(0)) + \cdots + B(H'_1(0) + G'_1(0) + F'_1(0)), \quad (2.29)$$

$$\psi'(L) = A^k B(H'_{k+1}(L) + G'_{k+1}(L) + F'_{k+1}(L)) + \cdots + B(H'_1(L) + G'_1(L) + F'_1(L)), \quad (2.30)$$

to determine the values of h'_i at $t_p(0; 0), t_p(0; L), t_p(L; 0), t_p(L; L)$, $i = 1, \dots, n$; $p = 1, \dots, k+1$. Now we continue to determine the other values of $h_i(t)$. (2.19) can be written as

$$\psi(x) - \tilde{G}(x) - \tilde{F}(x) = A^k B H_{k+1}(x) + [B, AB, \dots, A^{k-1}B] \hat{H}(x), x \in (0, L), \quad (2.31)$$

where

$$\hat{H}(x) = (H_1^T(x), \dots, H_k^T(x))^T.$$

From (2.4) and the implicit function existence theorem, we know that there exist n components of $\hat{H}(x)$ denoted as $H[n](x)$, s.t.

$$H[n](x) = \mathcal{H}(\psi(x) - \tilde{G}(x) - \tilde{F}(x), H_{k+1}(x), H[\hat{n}](x)), \quad (2.32)$$

where $H[\hat{n}](x)$ is the other components of $\hat{H}(x)$, and \mathcal{H} is a C^1 continuous function. For $H_{k+1}(x)$, we utilize the interpolation method to obtain the following equations:

$$H^-(t_{k+1}(L; x)) = p(L - x; H^-(t_{k+1}(L; 0)), -H'^-(t_{k+1}(L; 0))), \quad (2.33)$$

$$H^+(t_{k+1}(0; x)) = p(x; H^+(t_{k+1}(0; L)), H'^+(t_{k+1}(0; L))), \quad (2.34)$$

where $p(x; \alpha, \alpha')$, $x \in [0, L]$ is a polynomial determined by α, α' satisfying $p(x; \alpha, \alpha') = 0$, $x \in [0, T - \frac{t_0}{4}]$ and $p(L) = \alpha$, $p'(L) = \alpha'$. Similarly, for the components of $H[\hat{n}](x)$, we can also use the interpolation method to obtain the following equations:

$$H^-(\tilde{t}_p(L; x)) = p(x; H^-(\tilde{t}_p(L; 0)), H'^-(\tilde{t}_p(L; 0)), H^-(\tilde{t}_p(L; L)), H'^-(\tilde{t}_p(L; L))), \quad (2.35)$$

$$H^+(\tilde{t}_p(0; x)) = p(x; H^+(\tilde{t}_p(0; 0)), H^{+'}(\tilde{t}_p(0; 0)), H^+(\tilde{t}_p(0; L)), H^{+'}(\tilde{t}_p(0; L))), \quad (2.36)$$

where $p = 1, \dots, k$ and $p(x; \alpha, \alpha', \beta, \beta')$, $x \in [0, L]$ is a polynomial determined by $\alpha, \alpha', \beta, \beta'$ satisfying $p(0) = \alpha$, $p'(0) = \alpha'$, $p(L) = \beta$, $p'(L) = \beta'$. Finally, we use (2.32) to obtain the values of $H[n](x)$, $x \in [0, L]$. From the C^1 continuity of \mathcal{H} , (2.26) and (2.27), (2.29) and (2.30) and (2.4), we know that $h_i(t)$ is C^1 continuous in $[0, T]$. A solution $u(t, x)$ is obtained using the obtained boundary conditions and initial value conditions. Then

$$\begin{aligned} u(T, x) &= (u^-(\tilde{t}_1(L; x), L), u^+(t_1(0; x), 0))^T + F_1(x) \\ &= A(u^-(t_1(0; x), 0), u^+(\tilde{t}_2(L; x), L))^T + BH_1(x) + G_1(x) + F_1(x) \\ &= A(u^-(t_2, L), u^+(\tilde{t}_2, 0))^T + AF_2(x) + BH_1(x) + G_1(x) + F_1(x) \\ &\dots \\ &= A^k B(H_{k+1}(x) + G_{k+1}(x) + F_{k+1}(x)) + \dots + B(H_1(x) + G_1(x) + F_1(x)), \quad x \in [0, L]. \end{aligned} \quad (2.37)$$

Therefore, from (2.19), $u(T, x) = \psi(x)$ and thereby $h_i(t)$, $i = 1, \dots, n$ are exactly the control function that satisfies the requirement. \square

From the proof above, it is not difficult to obtain the C^1 estimate for $u(t, x)$ and $h_i(t)$, $i = 1, \dots, n$. From (2.14), we get

$$\|z_p(x; x_0) - 1\|_{C^0} \leq \|\tilde{a}\|_{C^1} (1 + C \|\tilde{a}\|_{C^0})^p. \quad (2.38)$$

Using (2.26), (2.27), (2.29), (2.30) and (2.38), we know the estimate of $h_i(t)$, $i = 1, \dots, n$ at $t_p(0; 0), t_p(0; L), t_p(L; 0), t_p(L; L)$, ($p = 1, \dots, k+1$).

$$\|h_i(t_p(\lambda_1; \lambda_2))\|_{C^1} \leq C_{A,k,\varepsilon_0} (\|\psi\|_{C^1} + \|\varphi\|_{C^1} + \|g\|_{C^1} + \|f^{(1)}\|_{C^1} \|f^{(2)}\|_{C^1}), \quad \lambda_1, \lambda_2 \in \{0, L\}. \quad (2.39)$$

From the defination $H_{k+1}(x)$ and $H[\hat{n}](x)$, we know that

$$\|H_{k+1}(x)\|_{C^1} \leq C_{A,k,\varepsilon_0} (\|\psi\|_{C^1} + \|\varphi\|_{C^1} + \|g\|_{C^1} + \|f^{(1)}\|_{C^1} \|f^{(2)}\|_{C^1}), \quad x \in [0, L], \quad (2.40)$$

and

$$\|H[\hat{n}](x)\|_{C^1} \leq C_{A,k,\varepsilon_0} (\|\psi\|_{C^1} + \|\varphi\|_{C^1} + \|g\|_{C^1} + \|f^{(1)}\|_{C^1} \|f^{(2)}\|_{C^1}), \quad x \in [0, L]. \quad (2.41)$$

Using (2.32), we can get the estimate of $H[n](x)$:

$$\|H[n](x)\|_{C^1} \leq C_{A,k,\varepsilon_0} (\|\psi\|_{C^1} + \|\varphi\|_{C^1} + \|g\|_{C^1} + \|f^{(1)}\|_{C^1} \|f^{(2)}\|_{C^1}), \quad x \in [0, L]. \quad (2.42)$$

Namely,

$$\|H(t)\|_{C^1} \leq C_{A,k,\varepsilon_0} (\|\psi\|_{C^1} + \|\varphi\|_{C^1} + \|g\|_{C^1} + \|f^{(1)}\|_{C^1} \|f^{(2)}\|_{C^1}). \quad (2.43)$$

Then we try to get the estimate of $u(t, x)$: From (2.1), we know that

$$\frac{du^+}{dx}(t_1(x; \xi), x) = f^{(1)+} \frac{df^{(2)+}}{dx}(t_1(x; \xi), x).$$

Thereby,

$$u^+(t_1(x; \xi), x) = u^+(0, \xi) + \int_{\xi}^x f^{(1)+} \frac{df^{(2)+}}{ds}(t_1(s; \xi), s) ds.$$

Therefore,

$$|u^+(t_1(x; \xi), x)| \leq C_{\varepsilon_0} \left(\|\varphi\|_{C^0} + \|f^{(1)}\|_{C^1} \|f^{(2)}\|_{C^1} \right).$$

Similarly, we can get the estimate of $u^-(\tilde{t}_1(x; \xi), x)$:

$$|u^-(\tilde{t}_1(x; \xi), x)| \leq C_{\varepsilon_0} \left(\|\varphi\|_{C^0} + \|f^{(1)}\|_{C^1} \|f^{(2)}\|_{C^1} \right).$$

Below we make inductive assumptions that for $j = 1, \dots, p-1$, the following estimates hold:

$$|u^+(t_j(x; \xi), x)| + |u^-(\tilde{t}_j(x; \xi), x)| \leq C_{A,k,\varepsilon_0} \left(\|\varphi\|_{C^1} + \|\psi\|_{C^1} + \|g\|_{C^1} + \left\| f^{(1)} \right\|_{C^1} \left\| f^{(2)} \right\|_{C^1} \right). \quad (2.44)$$

Then for $j = p$, we have

$$\frac{du^+}{dx}(t_p(x; \xi), x) = f^{(1)+} \frac{df^{(2)+}}{dx}(t_p(x; \xi), x),$$

and thereby

$$u^+(t_p(x; \xi), x) = u^+(t_p(0, \xi), 0) + \int_0^x f^{(1)+} \frac{df^{(2)+}}{ds}(t_p(s; \xi), s) ds.$$

Using (2.7) and the inductive assumption, we can get

$$u^+(t_p(0; \xi), 0) = A_2 u^-(\tilde{t}_{p-1}(0; \xi), 0) + G^+ + H^+,$$

and then

$$|u^+(t_p(x; \xi), x)| \leq C_{A,k,\varepsilon_0} \left(\|\varphi\|_{C^1} + \|\psi\|_{C^1} + \|g\|_{C^1} + \left\| f^{(1)} \right\|_{C^1} \left\| f^{(2)} \right\|_{C^1} \right).$$

Similarly, we can get the same estimate of $u^-(\tilde{t}_p(x; \xi), x)$. Therefore, (2.44) holds for $j = p$. Multiply both sides of (2.6) by $b(t, x)$ and then derive for t , denoting w^+ as the derivative of u^+ with respect to t , and we have

$$\frac{d}{dx} w^+ + \partial_t b w^+ = \partial_t \left(f^{(1)+} \frac{df^{(2)+}}{dx} \right).$$

Then we can get

$$w^+(t_1(x; \xi), x) = w^+(0, \xi) + \int_\xi^x \partial_t b w^+ ds + \int_\xi^x \partial_t f^{(1)+} \frac{df^{(2)}}{ds} ds + f^{(1)+} \partial_t f^{(2)+} \Big|_\xi^x - \int_\xi^x \partial_t f^{(2)+} \frac{df^{(1)+}}{ds} ds. \quad (2.45)$$

where

$$w^+(0, \xi) = -a\varphi'(\xi) + f^{(1)+}(\partial_t + a\partial_x) f^{(2)+}. \quad (2.46)$$

Thereby

$$|w^+(0, \xi)| \leq C_{\varepsilon_0} \left(\|\varphi\|_{C^1} + \left\| f^{(1)} \right\|_{C^1} \left\| f^{(2)} \right\|_{C^1} \right).$$

Then we can get the estimate of $w^+(t_1(x; \xi), x)$:

$$|w^+(t_1(x; \xi), x)| \leq \|\tilde{a}\|_{C^1} \int_\xi^x |w^+| ds + C_{\varepsilon_0} \left(\|\varphi\|_{C^1} + \left\| f^{(1)} \right\|_{C^1} \left\| f^{(2)} \right\|_{C^1} \right).$$

Using Gronwall's inequality, we can get

$$|w^+(t_1(x; \xi), x)| \leq C_{\varepsilon_0} \left(\|\varphi\|_{C^1} + \left\| f^{(1)} \right\|_{C^1} \left\| f^{(2)} \right\|_{C^1} \right).$$

Similarly, we can get the estimate of $w^-(\tilde{t}_1(x; \xi), x)$:

$$|w^-(\tilde{t}_1(x; \xi), x)| \leq C_{\varepsilon_0} \left(\|\varphi\|_{C^1} + \left\| f^{(1)} \right\|_{C^1} \left\| f^{(2)} \right\|_{C^1} \right).$$

Below we make inductive assumptions that for $j = 1, \dots, p-1$, the following estimates hold:

$$|w(t_j(x; \xi), x)| + |w^-(\tilde{t}_j(x; \xi), x)| \leq C_{A,k,\varepsilon_0} \left(\|\varphi\|_{C^1} + \|\psi\|_{C^1} + \|g\|_{C^1} + \left\| f^{(1)} \right\|_{C^1} \left\| f^{(2)} \right\|_{C^1} \right), \quad (2.47)$$

Then for $j = p$, we have

$$\begin{aligned} w^+(t_p(x; \xi), x) &= w^+(t_p(0, \xi), 0) + \int_0^x \partial_t b w^+ ds + \int_0^x \partial_t f^{(1)+} \frac{df^{(2)+}}{ds} ds \\ &\quad + f^{(1)+} \partial_t f^{(2)+} \Big|_0^x - \int_0^x \partial_t f^{(2)+} \frac{df^{(1)+}}{ds} ds, \end{aligned} \quad (2.48)$$

where

$$w^+(t_p(0; \xi), 0) = A_2 w^-(\tilde{t}_{p-1}(0; \xi), 0) + G^{+'} + H^{+'}. \quad (2.49)$$

and then using (2.47) and Gronwall' inequality, we can get (2.47) holds for $j = p$. Finally, we can get the estimate of $u(t, x)$:

$$\|u(t, x)\|_{C^1} \leq C_{A,k,\varepsilon_0} (\|\psi\|_{C^1} + \|\varphi\|_{C^1} + \|g\|_{C^1} + \|f^{(1)}\|_{C^1} \|f^{(2)}\|_{C^1}), \quad t \in [0, T], \quad x \in [0, L]. \quad (2.50)$$

Below we estimate the continuity paradigm of $h'_i(t)$, $\partial_x u(t, x)$ and $\partial_t u(t, x)$. For $H[\hat{n}]$ and H_{k+1} , using (2.33)- (2.36) , we have

$$|h'_i(t_1) - h'_i(t_2)| \leq C_{k,\varepsilon_0} (\|p\|_{C^2} |x_1 - x_2| + \|p\|_{C^1} \|\tilde{a}\|_{C^{1,1}} |x_1 - x_2|),$$

where $t_1 = t_p(\lambda; x_1)$, $t_2 = t_p(\lambda; x_2)$, $\lambda \in 0, L$, $x_1, x_2 \in [0, L]$ and

$$\|p\|_{C^2} \leq C \|h\|_{C^1} \leq C_{A,k,\varepsilon_0} (\|\psi\|_{C^1} + \|\varphi\|_{C^1} + \|g\|_{C^1} + \|f^{(1)}\|_{C^1} \|f^{(2)}\|_{C^1}).$$

Using (2.38), we can get

$$|x_1 - x_2| \leq C_{k,\varepsilon_0} |t_p(\lambda; x_1) - t_p(\lambda; x_2)| = C_{k,\varepsilon_0} |t_1 - t_2|.$$

For $H[n]$, using (2.32) and (2.42), we can get

$$|h'_i(t_1) - h'_i(t_2)| \leq C_A (\|\psi\|_{C^{1,1}} + \|\varphi\|_{C^{1,1}} + \|H[\hat{n}]\|_{C^{1,1}} + \|H_{k+1}\|_{C^{1,1}}).$$

Thereby, we can get the $C^{1,1}$ estimate of $h_i(t)$:

$$\|H(t)\|_{C^{1,1}} \leq C_{A,k,\varepsilon_0} (\|\psi\|_{C^{1,1}} + \|\varphi\|_{C^{1,1}} + \|g\|_{C^{1,1}} + \|f^{(1)}\|_{C^{1,1}} \|f^{(2)}\|_{C^{1,1}}).$$

Then we try to get the $C^{1,1}$ estimate of $u(t, x)$. We first consider $\omega(\eta \mid \partial_t u(\cdot, x))$. From (2.48) and (2.46), we know that

$$\begin{aligned} & |w^+(t_1(x; \xi_1), x) - w^+(t_1(x; \xi_2), x)| \leq C (|w^+(0, \xi_1) - w^+(0, \xi_2)| + \|u\|_{C^1} \|\tilde{a}\|_{C^{1,1}} |\xi_1 - \xi_2| \\ & + \|\tilde{a}\|_{C^1} \int_0^x |w^+(t_1(s; \xi_1), s) - w^+(t_1(s; \xi_2), s)| ds + \|f^{(1)}\|_{C^{1,1}} \|f^{(2)}\|_{C^{1,1}} |\xi_1 - \xi_2|), \end{aligned}$$

where

$$\begin{aligned} & |w^+(0, \xi_1) - w^+(0, \xi_2)| \leq C \left(\|\varphi\|_{C^{1,1}} + \|f^{(1)}\|_{C^{1,1}} \|f^{(2)}\|_{C^{1,1}} \right. \\ & \left. + (\|\varphi\|_{C^1} + \|f^{(1)}\|_{C^1} \|f^{(2)}\|_{C^1}) \|\tilde{a}\|_{C^{1,1}} \right) |\xi_1 - \xi_2|. \end{aligned}$$

Using Gronwall' inequality ,(2.14) and (2.38), we can get

$$|\xi_1 - \xi_2| \leq C_{\varepsilon_0} |t_1(x; \xi_1) - t_1(x; \xi_2)|,$$

and then

$$\begin{aligned} \omega(\eta \mid w^+(t_1(x; \cdot), x)) & \leq C_{A,k,\varepsilon_0} \left(\|\varphi\|_{C^{1,1}} + \|f^{(1)}\|_{C^{1,1}} \|f^{(2)}\|_{C^{1,1}} \right. \\ & \left. + (\|\psi\|_{C^1} + \|\varphi\|_{C^1} + \|g\|_{C^1} + \|f^{(1)}\|_{C^1} \|f^{(2)}\|_{C^1}) \|\tilde{a}\|_{C^{1,1}} \right) \eta \end{aligned}$$

Similarly, we can get the same estimate of $\omega(\eta \mid w^-(\tilde{t}_1(x; \cdot), x))$. Below we make inductive assumptions that for $j = 1, \dots, p-1$, the following estimates hold:

$$\begin{aligned} \omega(\eta \mid w^+(t_j(x; \cdot), x)) + \omega(\eta \mid w^-(\tilde{t}_j(x; \cdot), x)) & \leq C_{A,k,\varepsilon_0} (\|\varphi\|_{C^{1,1}} + \|\psi\|_{C^{1,1}} \\ & + \|f^{(1)}\|_{C^{1,1}} \|f^{(2)}\|_{C^{1,1}} + \|g\|_{C^{1,1}} + (\|\psi\|_{C^1} + \|\varphi\|_{C^1} + \|g\|_{C^1} + \|f^{(1)}\|_{C^1} \|f^{(2)}\|_{C^1}) \|\tilde{a}\|_{C^{1,1}}) \eta \end{aligned} \quad (2.51)$$

Then for $j = p$, from (2.48), we have

$$\begin{aligned} & |w^+(t_p(x; \xi_1), x) - w^+(t_p(x; \xi_2), x)| \leq C (|w^+(t_p(0; \xi_1), 0) - w^+(t_p(0; \xi_2), 0)| \\ & + \|\tilde{a}\|_{C^1} \int_0^x |w^+(\xi_1, s) - w^+(\xi_2, s)| ds \\ & + \|f^{(1)}\|_{C^{1,1}} \|f^{(2)}\|_{C^{1,1}} |\xi_1 - \xi_2| + \|u\|_{C^1} \|\tilde{a}\|_{C^{1,1}} |\xi_1 - \xi_2|) \end{aligned}$$

where from (2.49), we know that

$$\omega(\eta | w^+(t_p(0; \cdot), 0)) \leq C_A (\omega(\eta | w(t_{p-1}(x; \cdot), x)) + (\|g\|_{C^{1,1}} + \|h\|_{C^{1,1}}) \eta).$$

Then using Gronwall's inequality and (2.51) and similar estimate of $\omega(\eta | w^-(\tilde{t}_p(x; \cdot), x))$, we can get (2.51) holds for $j = p$. Next we consider $\omega(\eta | w^+(t_p(\cdot, \xi), \cdot))$. From (2.45) and (2.48), we know that

$$\omega(\eta | w(t_p(\cdot, \xi), \cdot)) \leq \left(\|\tilde{a}\|_{C^1} \|u\|_{C^1} + \left\| f^{(1)} \right\|_{C^{1,1}} \left\| f^{(2)} \right\|_{C^1} \right) \eta.$$

Similarly, we can get the same estimate of $\omega(\eta | w^-(\tilde{t}_p(\cdot, \xi), \cdot))$. Therefore, we get

$$\begin{aligned} \|\partial_t u\|_{C^{0,1}} &\leq C_{A,k,\varepsilon_0} \left(\|\varphi\|_{C^{1,1}} + \|\psi\|_{C^{1,1}} + \left\| f^{(1)} \right\|_{C^{1,1}} \left\| f^{(2)} \right\|_{C^{1,1}} + \|g\|_{C^{1,1}} \right. \\ &\quad \left. + (\|\psi\|_{C^1} + \|\varphi\|_{C^1} + \|g\|_{C^1} + \left\| f^{(1)} \right\|_{C^1} \left\| f^{(2)} \right\|_{C^1}) \|\tilde{a}\|_{C^{1,1}} \right) \end{aligned} \quad (2.52)$$

For $\partial_x u(t, x)$, from (2.1) we have

$$\|\partial_x u\|_{C^{0,1}} \leq C \left(\|\partial_t u\|_{C^{0,1}} + \|u\|_{C^1} \|\tilde{a}\|_{C^1} + \left\| f^{(1)} \right\|_{C^{1,1}} \left\| f^{(2)} \right\|_{C^{1,1}} \right).$$

Thereby, we can get

$$\begin{aligned} \|u\|_{C^{1,1}} &\leq C_{A,k,\varepsilon_0} \left(\|\varphi\|_{C^{1,1}} + \|\psi\|_{C^{1,1}} + \left\| f^{(1)} \right\|_{C^{1,1}} \left\| f^{(2)} \right\|_{C^{1,1}} + \|g\|_{C^{1,1}} \right. \\ &\quad \left. + (\|\psi\|_{C^1} + \|\varphi\|_{C^1} + \|g\|_{C^1} + \left\| f^{(1)} \right\|_{C^1} \left\| f^{(2)} \right\|_{C^1}) \|\tilde{a}\|_{C^{1,1}} \right) \end{aligned} \quad (2.53)$$

Then we consider the continuity of control functions and solutions with regard to the coefficients of equations. Consider another controlling problem with the coefficients $\bar{a}(t, x)$, $\bar{f}^{(1)}(t, x)$, $\bar{f}^{(2)}(t, x)$, $\bar{g}(t, x)$ and its solution $v(t, x)$, denoting $y = \partial_t v$, where we assume that the values of these coefficients are the same as those of $a(t, x)$, $f^{(1)}(t, x)$, $f^{(2)}(t, x)$, $g(t, x)$ at $t = 0$ and $t = L$ and thereby we can select the same set of functions $\tilde{H}(t)$ to satisfy the compatibility. We first consider the initial boundary value problem (2.6) and (2.7) with the coefficients $\bar{a}(t, x)$, $\bar{f}^{(1)}(t, x)$, $\bar{f}^{(2)}(t, x)$, $\bar{g}(t)$. From (2.14), we know that

$$\|t_1(x; x_0) - \bar{t}_1(x; x_0)\|_{C^0} \leq C_{\varepsilon_0} \|a - \bar{a}\|_{C^0}.$$

Select a point (t_0, L) , where $t_0 = t_1(L; \xi)$ for some ξ , and consider the characteristic curve passing through this point, denoting ξ as the point where this characteristic curve $t_1(x; t_0)$ intersects with $t = 0$ and $\bar{\xi}$ as the point where this characteristic curve $\bar{t}_1(x; t_0)$ intersects with $t = 0$, we have

$$|x_1 - \bar{x}_1| \leq C_{\varepsilon_0} \|a - \bar{a}\|_{C^0},$$

and

$$\begin{aligned} \tilde{u}^+(t_1(L; \xi), L) &= \tilde{u}^+(0, \xi) + \int_{\xi}^L f^{(1)+} \frac{df^{(2)+}}{ds}(t_1(s; \xi), s) ds, \\ \tilde{v}^+(\bar{t}_1(L; \bar{\xi}), L) &= \tilde{v}^+(0, \bar{\xi}) + \int_{\bar{\xi}}^L \bar{f}^{(1)+} \frac{d\bar{f}^{(2)+}}{ds}(\bar{t}_1(s; \bar{\xi}), s) ds. \end{aligned}$$

Thereby,

$$\begin{aligned} |\tilde{u}^+(t_1(L; \xi), L) - \tilde{v}^+(\bar{t}_1(L; \bar{\xi}), L)| &\leq |\tilde{v}^+(0, \bar{\xi}) - \tilde{u}^+(0, \xi)| \\ &\quad + C \left((\|f^{(1)}\|_{C^1} \|f^{(2)}\|_{C^1} + \|\bar{f}^{(1)}\|_{C^1} \|\bar{f}^{(2)}\|_{C^1}) |\xi - \bar{\xi}| \right. \\ &\quad \left. + \|\bar{f}^{(2)}\|_{C^1} \|f^{(1)} - \bar{f}^{(1)}\|_{C^0} + \|\bar{f}^{(2)}\|_{C^1} \|f^{(1)}\|_{C^1} \|t_1 - \bar{t}_1\|_{C^0} \right. \\ &\quad \left. + \|f^{(1)}\|_{C^0} \|f^{(2)} - \bar{f}^{(2)}\|_{C^1} + \|f^{(1)}\|_{C^0} \|\bar{f}^{(2)}\|_{C^{1,1}} \|t_1 - \bar{t}_1\|_{C^0} \right. \\ &\quad \left. + \|f^{(1)}\|_{C^0} \|f^{(2)}\|_{C^1} \|a - \bar{a}\|_{C^0} \right). \end{aligned}$$

where

$$|\tilde{v}^+(0, \bar{\xi}) - \tilde{u}^+(0, \xi)| = |\varphi(\xi) - \varphi(\bar{\xi})| \leq \|\varphi\|_{C^1} |\xi - \bar{\xi}|,$$

$$\|t_1 - \bar{t}_1\|_{C^0} = \sup_{0 \leq s \leq L} |\bar{t}_1(s; \bar{\xi}) - t_1(s; \xi)| \leq C_{\varepsilon_0} \|a - \bar{a}\|_{C^0}.$$

If the characteristic curve $\bar{t}_2(x; \bar{\xi})$ intersects with $x = 0$ at $(\bar{t}_2(0; \bar{\xi}), 0)$, we have

$$\tilde{v}^+(\bar{t}_2(L; \bar{\xi}), L) = \tilde{v}^+(\bar{t}_2(0; \bar{\xi}), 0) + \int_0^L \bar{f}^{(1)+} \frac{d\bar{f}^{(2)+}}{ds}(\bar{t}_2(s; \bar{\xi}), s) ds,$$

and

$$|\xi| \leq C \|a - \bar{a}\|_{C^0},$$

$$|\bar{t}_2(0; \bar{\xi})| \leq C \|a - \bar{a}\|_{C^0},$$

$$\begin{aligned} |\tilde{u}^+(0, \xi) - \tilde{v}^+(\bar{t}_2(0; \bar{\xi}), 0)| &\leq |\tilde{u}^+(0, \xi) - \tilde{u}^+(0, 0)| + |\tilde{u}^+(0, 0) - \tilde{v}^+(0, 0)| + |\tilde{v}^+(0, 0) - \tilde{v}^+(\bar{t}_2(0; \bar{\xi}), 0)| \\ &\leq \|\varphi\|_{C^1} |\xi| + \|\tilde{v}\|_{C^1} |\bar{t}_2(0; \bar{\xi})|. \end{aligned}$$

Thereby, we can get

$$\begin{aligned} |\tilde{u}^+(t_0, L) - \tilde{v}^+(t_0, L)| &\leq C \left((\|\varphi\|_{C^1} + \|g\|_{C^1} + \|\bar{g}\|_{C^1} + \|f^{(1)}\|_{C^1} \|f^{(2)}\|_{C^{1,1}} + \|\bar{f}^{(1)}\|_{C^1} \|\bar{f}^{(2)}\|_{C^{1,1}}) \|a - \bar{a}\|_{C^0} \right. \\ &\quad \left. + \|\bar{f}^{(2)}\|_{C^1} \|f^{(1)} - \bar{f}^{(1)}\|_{C^0} + \|f^{(1)}\|_{C^0} \|f^{(2)} - \bar{f}^{(2)}\|_{C^1} \right). \end{aligned}$$

Similarly, we can get the same estimate of $|\tilde{u}^-(\tilde{t}_0, 0) - \tilde{v}^-(\tilde{t}_0, 0)|$. Then we make inductive assumptions that for $j = 1, \dots, p-1$, the following estimates hold:

$$\begin{aligned} |\tilde{u}^+(t_0, L) - \tilde{v}^+(t_0, L)| &\leq C \left((\|\varphi\|_{C^1} + \|g\|_{C^1} + \|\bar{g}\|_{C^1} + \|f^{(1)}\|_{C^1} \|f^{(2)}\|_{C^{1,1}} + \|\bar{f}^{(1)}\|_{C^1} \|\bar{f}^{(2)}\|_{C^{1,1}}) \|a - \bar{a}\|_{C^0} \right. \\ &\quad \left. + \|g - \bar{g}\|_{C^0} + \|\bar{f}^{(2)}\|_{C^1} \|f^{(1)} - \bar{f}^{(1)}\|_{C^0} + \|f^{(1)}\|_{C^0} \|f^{(2)} - \bar{f}^{(2)}\|_{C^1} \right). \end{aligned}$$

and

$$\begin{aligned} |\tilde{u}^-(\tilde{t}_0, 0) - \tilde{v}^-(\tilde{t}_0, 0)| &\leq C \left((\|\varphi\|_{C^1} + \|g\|_{C^1} + \|\bar{g}\|_{C^1} + \|f^{(1)}\|_{C^1} \|f^{(2)}\|_{C^{1,1}} + \|\bar{f}^{(1)}\|_{C^1} \|\bar{f}^{(2)}\|_{C^{1,1}}) \|a - \bar{a}\|_{C^0} \right. \\ &\quad \left. + \|g - \bar{g}\|_{C^0} + \|\bar{f}^{(2)}\|_{C^1} \|f^{(1)} - \bar{f}^{(1)}\|_{C^0} + \|f^{(1)}\|_{C^0} \|f^{(2)} - \bar{f}^{(2)}\|_{C^1} \right). \end{aligned}$$

where $t_0 = t_j(L; \xi)$ and $\tilde{t}_0 = \tilde{t}_j(0; \xi)$ for some ξ . Then for $j = p$, from (2.50), we have

$$\tilde{u}^+(t_p(L; \xi), L) = \tilde{u}^+(t_p(0; \xi), 0) + \int_0^L f^{(1)+} \frac{d\bar{f}^{(2)+}}{ds}(t_p(s; \xi), s) ds,$$

$$\tilde{v}^+(\bar{t}_p(L; \bar{\xi}), L) = \tilde{v}^+(t_p(0; \xi), 0) + \int_0^L \bar{f}^{(1)+} \frac{d\bar{f}^{(2)+}}{ds}(\bar{t}_p(s; \bar{\xi}), s) ds,$$

where

$$\tilde{u}^+(t_p(0; \xi), 0) = A_2 \tilde{u}^-(\tilde{t}_{p-1}(0; \xi), 0) + G^+(t_p(0; \xi)) + H^+(t_p(0; \xi)),$$

$$\tilde{v}^+(\bar{t}_p(0; \bar{\xi}), 0) = A_2 \tilde{v}^-(\tilde{t}_{p-1}(0; \bar{\xi}), 0) + \bar{g}_s(\bar{t}_p(0; \bar{\xi})) + H^+(\bar{t}_p(0; \bar{\xi})).$$

Therefore, using the inductive assumptions, we can get

$$\begin{aligned} |\tilde{u}^+(t_p(0; \xi), 0) - \tilde{v}^+(\bar{t}_p(0; \bar{\xi}), 0)| &\leq C \left((\|\varphi\|_{C^1} + \|g\|_{C^1} + \|\bar{g}\|_{C^1}) \|a - \bar{a}\|_{C^0} \right. \\ &\quad \left. + \|g - \bar{g}\|_{C^0} + \|\bar{f}^{(2)}\|_{C^1} \|f^{(1)} - \bar{f}^{(1)}\|_{C^0} + \|f^{(1)}\|_{C^0} \|f^{(2)} - \bar{f}^{(2)}\|_{C^1} \right). \end{aligned}$$

Then using the same method as $j = 1, \dots, p-1$, we can get that the above estimate holds for $j = p$. And thereby we can get

$$\begin{aligned} \|\tilde{u} - \tilde{v}\|_{C^0} &\leq C \left((\|\varphi\|_{C^1} + \|g\|_{C^1} + \|\bar{g}\|_{C^1} + \|f^{(1)}\|_{C^1} \|f^{(2)}\|_{C^{1,1}} + \|\bar{f}^{(1)}\|_{C^1} \|\bar{f}^{(2)}\|_{C^{1,1}}) \|a - \bar{a}\|_{C^0} \right. \\ &\quad \left. + \|g - \bar{g}\|_{C^0} + \|\bar{f}^{(2)}\|_{C^1} \|f^{(1)} - \bar{f}^{(1)}\|_{C^0} + \|f^{(1)}\|_{C^0} \|f^{(2)} - \bar{f}^{(2)}\|_{C^1} \right). \end{aligned}$$

Considering the point (t_0, L) , where $t_0 = t_0(L; \xi)$ for some ξ , and the characteristic curve $t_1(x; t_0)$ passing through this point and intersecting $t = 0$ at ξ , as well as the characteristic curve $\bar{t}_1(x; t_0)$ passing through this point and intersecting $t = 0$ at $\bar{\xi}$, we have

$$\begin{aligned}\tilde{w}^+(t_1(L; \xi), L) &= \tilde{w}^+(0, \xi) + \int_{\xi}^L \partial_t b \tilde{w}^+ ds + \int_{\xi}^L \partial_t f^{(1)+} \frac{df^{(2)+}}{ds} ds + f^{(1)+} \partial_t f^{(2)+} \Big|_{\xi}^L - \int_{\xi}^L \partial_t f^{(2)+} \frac{df^{(1)+}}{ds} ds, \\ \tilde{y}^+(\bar{t}_1(L; \bar{\xi}), L) &= \tilde{y}^+(0, \bar{\xi}) + \int_{\bar{\xi}}^L \partial_t \bar{b} \tilde{y}^+ ds + \int_{\bar{\xi}}^L \partial_t \bar{f}^{(1)+} \frac{d\bar{f}^{(2)+}}{ds} ds + \bar{f}^{(1)+} \partial_t \bar{f}^{(2)+} \Big|_{\bar{\xi}}^L - \int_{\bar{\xi}}^L \partial_t \bar{f}^{(2)+} \frac{d\bar{f}^{(1)+}}{ds} ds,\end{aligned}$$

where

$$\begin{aligned}\tilde{w}^+(0, \xi) &= -a\varphi^{+'}(\xi) + f^{(1)+} (\partial_t + a\partial_x) f^{(2)+}, \\ \tilde{y}^+(0, \bar{\xi}) &= -\bar{a}\varphi^{+'}(\bar{\xi}) + \bar{f}^{(1)+} (\partial_t + \bar{a}\partial_x) \bar{f}^{(2)+}.\end{aligned}$$

Then we have

$$\begin{aligned}& |\tilde{w}^+(t_1(L; \xi), L) - \tilde{y}^+(\bar{t}_1(L; \bar{\xi}), L)| \\ & \leq C_{\varepsilon_0} \left(|\tilde{w}^+(0, \xi) - \tilde{y}^+(0, \bar{\xi})| + \|\tilde{a}\|_{C^1} \int_{\xi}^L |\tilde{w}^+(t_1(s; \xi), s) - \tilde{y}^+(\bar{t}_1(s; \bar{\xi}), s)| ds \right. \\ & \quad + (\|\tilde{a}\|_{C^1} \|\tilde{v}\|_{C^1} + \|\bar{f}^{(1)}\|_{C^1} \|\bar{f}^{(2)}\|_{C^1} + \|\bar{f}^{(1)}\|_{C^0} \|\bar{f}^{(2)}\|_{C^{1,1}}) |\xi - \bar{\xi}| \\ & \quad + \|\tilde{a}\|_{C^{1,1}} \|\tilde{u}\|_{C^1} \|t_1 - \bar{t}_1\|_{C^0} + \|\tilde{u}\|_{C^1} \|a - \bar{a}\|_{C^1} \\ & \quad + \|f^{(1)} - \bar{f}^{(1)}\|_{C^1} \|\bar{f}^{(2)}\|_{C^1} + \|f^{(1)} - \bar{f}^{(1)}\|_{C^1} \|f^{(2)}\|_{C^1} \\ & \quad + \|\bar{f}^{(1)}\|_{C^1} \|f^{(2)} - \bar{f}^{(2)}\|_{C^1} + \|f^{(1)}\|_{C^1} \|f^{(2)} - \bar{f}^{(2)}\|_{C^1} \\ & \quad + \|f^{(1)}\|_{C^1} \|f^{(2)}\|_{C^1} \|t_1 - \bar{t}_1\|_{C^0} + \|\bar{f}^{(1)}\|_{C^1} \|f^{(2)}\|_{C^1} \|t_1 - \bar{t}_1\|_{C^0} \\ & \quad + \|\bar{f}^{(1)}\|_{C^1} \|\bar{f}^{(2)}\|_{C^1} \|t_1 - \bar{t}_1\|_{C^0} + \|\bar{f}^{(1)}\|_{C^1} \|\bar{f}^{(2)}\|_{C^1} \|a - \bar{a}\|_{C^1} \\ & \quad \left. + \|\bar{f}^{(1)}\|_{C^1} \|\bar{f}^{(2)}\|_{C^{1,1}} \|t_1 - \bar{t}_1\|_{C^0} \right).\end{aligned}$$

where

$$\begin{aligned}|\tilde{w}^+(0, \xi) - \tilde{y}^+(0, \bar{\xi})| &\leq C_{\varepsilon_0} \left(\|a - \bar{a}\|_{C^0} \|\varphi\|_{C^1} + \|\bar{a}\|_{C^1} \|\varphi\|_{C^1} |\xi - \bar{\xi}| + \|\varphi\|_{C^{1,1}} |\xi - \bar{\xi}| \right. \\ & \quad + \|f^{(1)} - \bar{f}^{(1)}\|_{C^0} \|\bar{f}^{(2)}\|_{C^1} + \|\bar{f}^{(1)}\|_{C^0} \|f^{(2)} - \bar{f}^{(2)}\|_{C^1} \\ & \quad + \|\bar{f}^{(1)}\|_{C^1} \|\bar{f}^{(2)}\|_{C^1} \|t_1 - \bar{t}_1\|_{C^0} + \|\bar{f}^{(1)}\|_{C^0} \|\bar{f}^{(2)}\|_{C^{1,1}} \|t_1 - \bar{t}_1\|_{C^0} \\ & \quad \left. + \|\bar{f}^{(1)}\|_{C^0} \|\bar{f}^{(2)}\|_{C^1} \|a - \bar{a}\|_{C^0} \right).\end{aligned}$$

Using Gronwall's inequality, we can get

$$\begin{aligned}& |\tilde{w}^+(t_1(L; \xi), L) - \tilde{y}^+(\bar{t}_1(L; \bar{\xi}), L)| \leq C_{\varepsilon_0} \left(\|a - \bar{a}\|_{C^0} \|\varphi\|_{C^1} + \|\bar{a}\|_{C^1} \|\varphi\|_{C^1} |\xi - \bar{\xi}| + \|\varphi\|_{C^{1,1}} |\xi - \bar{\xi}| \right. \\ & \quad + (\|\tilde{a}\|_{C^1} \|\tilde{v}\|_{C^1} + \|\bar{f}^{(1)}\|_{C^1} \|\bar{f}^{(2)}\|_{C^1} + \|\bar{f}^{(1)}\|_{C^0} \|\bar{f}^{(2)}\|_{C^{1,1}}) |\xi - \bar{\xi}| \\ & \quad + \|\tilde{a}\|_{C^{1,1}} \|\tilde{u}\|_{C^1} \|t_1 - \bar{t}_1\|_{C^0} + \|\tilde{u}\|_{C^1} \|a - \bar{a}\|_{C^1} \\ & \quad + \|f^{(1)} - \bar{f}^{(1)}\|_{C^1} \|\bar{f}^{(2)}\|_{C^1} + \|f^{(1)} - \bar{f}^{(1)}\|_{C^1} \|f^{(2)}\|_{C^1} \\ & \quad + \|\bar{f}^{(1)}\|_{C^1} \|f^{(2)} - \bar{f}^{(2)}\|_{C^1} + \|f^{(1)}\|_{C^1} \|f^{(2)} - \bar{f}^{(2)}\|_{C^1} \\ & \quad + \|f^{(1)}\|_{C^1} \|f^{(2)}\|_{C^1} \|t_1 - \bar{t}_1\|_{C^0} + \|\bar{f}^{(1)}\|_{C^1} \|f^{(2)}\|_{C^1} \|t_1 - \bar{t}_1\|_{C^0} \\ & \quad + \|\bar{f}^{(1)}\|_{C^1} \|\bar{f}^{(2)}\|_{C^1} \|t_1 - \bar{t}_1\|_{C^0} + \|\bar{f}^{(1)}\|_{C^1} \|\bar{f}^{(2)}\|_{C^1} \|a - \bar{a}\|_{C^1} \\ & \quad \left. + \|\bar{f}^{(1)}\|_{C^1} \|\bar{f}^{(2)}\|_{C^{1,1}} \|t_1 - \bar{t}_1\|_{C^0} \right).\end{aligned}$$

If the characteristic curve $\bar{t}_2(x; \bar{\xi})$ intersects with $x = 0$ at $(\bar{t}_2(0; \bar{\xi}), 0)$, we have

$$\tilde{y}^-(\bar{t}_2(L; \bar{\xi}), L) = \tilde{y}^-(\bar{t}_2(0, \bar{\xi}), 0) + \int_0^L \partial_t \bar{b} \tilde{y}^- ds + \int_0^L \partial_t \bar{f}^{(1)+} \frac{d\bar{f}^{(2)+}}{ds} ds + \bar{f}^{(1)+} \partial_t \bar{f}^{(2)+} \Big|_0^L - \int_0^L \partial_t \bar{f}^{(2)+} \frac{d\bar{f}^{(1)+}}{ds} ds,$$

and

$$\begin{aligned} |\tilde{y}^-(\bar{t}_2(0, \bar{\xi}), 0) - \tilde{w}^+(0, \xi)| &\leq |\tilde{y}^-(\bar{t}_2(0, \bar{\xi}), 0) - \tilde{y}^-(0, 0)| + |\tilde{w}^+(0, 0) - \tilde{w}^+(0, \xi)| \\ &\leq C_{\varepsilon_0} (\|\tilde{v}\|_{C^{1,1}} + \|\tilde{u}\|_{C^{1,1}}) \|a - \bar{a}\|_{C^1} \end{aligned}$$

Therefore, we can get

$$\begin{aligned} |\tilde{w}^+(t_1(L; \xi), L) - \tilde{y}^+(\bar{t}_1(L; \bar{\xi}), L)| &\leq C_{\varepsilon_0} \left(\|a - \bar{a}\|_{C^0} \|\varphi\|_{C^1} + \|\bar{a}\|_{C^1} \|\varphi\|_{C^1} |\xi - \bar{\xi}| + \|\varphi\|_{C^{1,1}} |\xi - \bar{\xi}| \right. \\ &\quad + (\|\tilde{a}\|_{C^1} \|\tilde{v}\|_{C^1} + \|\bar{f}^{(1)}\|_{C^1} \|\bar{f}^{(2)}\|_{C^1} + \|\bar{f}^{(1)}\|_{C^0} \|\bar{f}^{(2)}\|_{C^{1,1}}) |\xi - \bar{\xi}| \\ &\quad + \|\tilde{a}\|_{C^{1,1}} \|\tilde{u}\|_{C^1} \|t_1 - \bar{t}_1\|_{C^0} + (\|\tilde{u}\|_{C^{1,1}} + \|\tilde{v}\|_{C^{1,1}}) \|a - \bar{a}\|_{C^1} \\ &\quad + \|f^{(1)} - \bar{f}^{(1)}\|_{C^1} \|\bar{f}^{(2)}\|_{C^1} + \|f^{(1)} - \bar{f}^{(1)}\|_{C^1} \|f^{(2)}\|_{C^1} \\ &\quad + \|\bar{f}^{(1)}\|_{C^1} \|f^{(2)} - \bar{f}^{(2)}\|_{C^1} + \|f^{(1)}\|_{C^1} \|f^{(2)} - \bar{f}^{(2)}\|_{C^1} \\ &\quad + \|f^{(1)}\|_{C^1} \|f^{(2)}\|_{C^1} \|t_1 - \bar{t}_1\|_{C^0} + \|\bar{f}^{(1)}\|_{C^1} \|f^{(2)}\|_{C^1} \|t_1 - \bar{t}_1\|_{C^0} \\ &\quad + \|\bar{f}^{(1)}\|_{C^1} \|\bar{f}^{(2)}\|_{C^1} \|t_1 - \bar{t}_1\|_{C^0} + \|\bar{f}^{(1)}\|_{C^1} \|\bar{f}^{(2)}\|_{C^1} \|a - \bar{a}\|_{C^1} \\ &\quad \left. + \|\bar{f}^{(1)}\|_{C^1} \|\bar{f}^{(2)}\|_{C^{1,1}} \|t_1 - \bar{t}_1\|_{C^0} \right). \end{aligned}$$

Similarly, we can get the same estimate of $|\tilde{w}^-(\tilde{t}_1(0; \xi), 0) - \tilde{y}^-(\bar{t}_1(0; \bar{\xi}), 0)|$. Then we make inductive assumptions that for $j = 1, \dots, p-1$, the following estimates hold:

$$\begin{aligned} &|\tilde{w}^+(t_0, L) - \tilde{y}^+(t_0, L)| \\ &\leq C_{\varepsilon_0} \left((\|f^{(1)}\|_{C^1} + \|f^{(2)}\|_{C^1} + \|\bar{f}^{(1)}\|_{C^1} + \|\bar{f}^{(2)}\|_{C^1}) (\|f^{(2)} - \bar{f}^{(2)}\|_{C^1} + \|f^{(1)} - \bar{f}^{(1)}\|_{C^1}) \right. \\ &\quad + (\|\varphi\|_{C^{1,1}} + \|g\|_{C^{1,1}} + \|\bar{g}\|_{C^{1,1}} + (\|f^{(1)}\|_{C^{1,1}} + \|\bar{f}^{(1)}\|_{C^{1,1}}) (\|f^{(2)}\|_{C^{1,1}} + \|\bar{f}^{(2)}\|_{C^{1,1}})) \|a - \bar{a}\|_{C^1} \\ &\quad \left. + \|g^{(1)} - \bar{g}^{(1)}\|_{C^1} \right), \end{aligned}$$

and

$$\begin{aligned} &|\tilde{w}^-(\tilde{t}_0, 0) - \tilde{y}^-(\tilde{t}_0, 0)| \\ &\leq C_{\varepsilon_0} \left((\|f^{(1)}\|_{C^1} + \|f^{(2)}\|_{C^1} + \|\bar{f}^{(1)}\|_{C^1} + \|\bar{f}^{(2)}\|_{C^1}) (\|f^{(2)} - \bar{f}^{(2)}\|_{C^1} + \|f^{(1)} - \bar{f}^{(1)}\|_{C^1}) \right. \\ &\quad + (\|\varphi\|_{C^{1,1}} + \|g\|_{C^{1,1}} + \|\bar{g}\|_{C^{1,1}} + (\|f^{(1)}\|_{C^{1,1}} + \|\bar{f}^{(1)}\|_{C^{1,1}}) (\|f^{(2)}\|_{C^{1,1}} + \|\bar{f}^{(2)}\|_{C^{1,1}})) \|a - \bar{a}\|_{C^1} \\ &\quad \left. + \|g^{(1)} - \bar{g}^{(1)}\|_{C^1} \right). \end{aligned}$$

where $t_0 = t_j(L; \xi)$ for some ξ . Then for $j = p$, we have

$$\begin{aligned} \tilde{w}^+(t_p(L; \xi), L) &= \tilde{w}^+(t_p(0, \xi), 0) + \int_0^L \partial_t b \tilde{w}^+ ds + \int_0^L \partial_t f^{(1)+} \frac{df^{(2)}}{ds} ds + f^{(1)+} \partial_t f^{(2)+} \Big|_0^L - \int_0^L \partial_t f^{(2)+} \frac{df^{(1)+}}{ds} ds, \\ \tilde{y}^-(\bar{t}_p(L; \bar{\xi}), L) &= \tilde{y}^-(\bar{t}_p(0, \bar{\xi}), 0) + \int_0^L \partial_t \bar{b} \tilde{y}^- ds + \int_0^L \partial_t \bar{f}^{(1)+} \frac{d\bar{f}^{(2)}}{ds} ds + \bar{f}^{(1)+} \partial_t \bar{f}^{(2)+} \Big|_0^L - \int_0^L \partial_t \bar{f}^{(2)+} \frac{d\bar{f}^{(1)+}}{ds} ds, \end{aligned}$$

where

$$\begin{aligned} \tilde{w}^+(t_p(0; \xi), 0) &= A_2 \tilde{w}^-(t_{p-1}(0; \xi), 0) + G^{+'}(t_p(0; \xi)) + H^{+'}(t_p(0; \xi)), \\ \tilde{y}^-(\bar{t}_p(0; \bar{\xi}), 0) &= A_2 \tilde{y}^-(\bar{t}_{p-1}(0; \bar{\xi}), 0) + \bar{G}^{+'}(\bar{t}_p(0; \bar{\xi})) + H^{+'}(\bar{t}_p(0; \bar{\xi})). \end{aligned}$$

Therefore, using the inductive assumptions, we can get

$$\begin{aligned} &|\tilde{w}^+(t_p(0; \xi), 0) - \tilde{y}^+(\bar{t}_p(0; \bar{\xi}), 0)| \leq C_{A,k,\varepsilon_0} \left((\|\tilde{u}\|_{C^{1,1}} + \|\tilde{v}\|_{C^{1,1}}) \|a - \bar{a}\|_{C^0} \right. \\ &\quad + (\|f^{(1)}\|_{C^1} + \|f^{(2)}\|_{C^1} + \|\bar{f}^{(1)}\|_{C^1} + \|\bar{f}^{(2)}\|_{C^1}) (\|f^{(2)} - \bar{f}^{(2)}\|_{C^1} + \|f^{(1)} - \bar{f}^{(1)}\|_{C^1}) \\ &\quad + (\|\varphi\|_{C^{1,1}} + \|g\|_{C^{1,1}} + \|\bar{g}\|_{C^{1,1}} + (\|f^{(1)}\|_{C^{1,1}} + \|\bar{f}^{(1)}\|_{C^{1,1}}) (\|f^{(2)}\|_{C^{1,1}} + \|\bar{f}^{(2)}\|_{C^{1,1}})) \|a - \bar{a}\|_{C^1} \\ &\quad \left. + \|g^{(1)} - \bar{g}^{(1)}\|_{C^1} \right). \end{aligned}$$

Then using the same method as $j = 1, \dots, p-1$, we can get that the above estimate holds for $j = p$. And thereby we can get

$$\begin{aligned} \|\tilde{u} - \tilde{v}\|_{C^1} &\leq C_{A,k,\varepsilon_0} \left((\|f^{(1)}\|_{C^1} + \|f^{(2)}\|_{C^1} + \|\bar{f}^{(1)}\|_{C^1} + \|\bar{f}^{(2)}\|_{C^1}) (\|f^{(2)} - \bar{f}^{(2)}\|_{C^1} + \|f^{(1)} - \bar{f}^{(1)}\|_{C^1}) \right. \\ &\quad + (\|\varphi\|_{C^{1,1}} + \|g\|_{C^{1,1}} + \|\bar{g}\|_{C^{1,1}} + (\|f^{(1)}\|_{C^{1,1}} + \|\bar{f}^{(1)}\|_{C^{1,1}}) (\|f^{(2)}\|_{C^{1,1}} + \|\bar{f}^{(2)}\|_{C^{1,1}})) \|a - \bar{a}\|_{C^1} \\ &\quad \left. + \|g - \bar{g}\|_{C^1} \right). \end{aligned}$$

Then we consider the value and derivative of $h_i(t_p(0;0)), h_i(t_p(0;L)), h_i(t_p(L;0)), h_i(t_p(L;L))$. From (2.19), we know that

$$|h_i(t_p(\lambda_1; \lambda_2)) - \bar{h}_i(\bar{t}_p(\lambda_1; \lambda_2))| \leq \|\tilde{u} - \tilde{v}\|_{C^0} + \sum_{p=1}^{k+1} |G_p(\lambda_2) - \bar{G}_p(\lambda_2)| + \sum_{p=1}^{k+1} |F_p(\lambda_2) - \bar{F}_p(\lambda_2)|,$$

where $\lambda_1, \lambda_2 = 0, L$. And

$$\begin{aligned} |G_p(\lambda_2) - \bar{G}_p(\lambda_2)| &\leq \|g - \bar{g}\|_{C^0} + \|g\|_{C^1} \|a - \bar{a}\|_{C^0}, \\ |F_p(\lambda_2) - \bar{F}_p(\lambda_2)| &\leq C_{\varepsilon_0, k} \left((\|f^{(1)}\|_{C^1} + \|\bar{f}^{(1)}\|_{C^1}) (\|f^{(2)}\|_{C^{1,1}} + \|\bar{f}^{(2)}\|_{C^{1,1}}) \|a - \bar{a}\|_{C^0} \right. \\ &\quad \left. + \|f^{(1)} - \bar{f}^{(1)}\|_{C^0} \|f^{(2)}\|_{C^1} + \|f^{(2)} - \bar{f}^{(2)}\|_{C^1} \|\bar{f}^{(1)}\|_{C^0} \right). \end{aligned}$$

For the derivative, we have

$$|h'_i(t_p(\lambda_1; \lambda_2)) - \bar{h}'_i(\bar{t}_p(\lambda_1; \lambda_2))| \leq C_{\varepsilon_0, k} \left(\sum_{p=1}^{k+1} |H'_p(\lambda_2) - \bar{H}'_p(\lambda_2)| + \|h\|_{C^1} \left(\sum_{p=1}^{k+1} |z'_p(\lambda_1; \lambda_2) - \bar{z}'_p(\lambda_1; \lambda_2)| \right) \right)$$

where

$$\begin{aligned} |H'_p(\lambda_2) - \bar{H}'_p(\lambda_2)| &\leq C_{A, \varepsilon_0, k} \left(\|\tilde{u} - \tilde{v}\|_{C^1} + \sum_{p=1}^{k+1} |G'_p(\lambda_2) - \bar{G}'_p(\lambda_2)| + \sum_{p=1}^{k+1} |F'_p(\lambda_2) - \bar{F}'_p(\lambda_2)| \right), \\ |z'_p(\lambda_1; \lambda_2) - \bar{z}'_p(\lambda_1; \lambda_2)| &\leq C_{\varepsilon_0, k} (\|a - \bar{a}\|_{C^1} + \|\tilde{a}\|_{C^{1,1}} \|a - \bar{a}\|_{C^0}), \end{aligned}$$

and

$$\begin{aligned} |G'_p(\lambda_2) - \bar{G}'_p(\lambda_2)| &\leq C_{\varepsilon_0, k} \left(\|g - \bar{g}\|_{C^1} + \|g\|_{C^{1,1}} \|a - \bar{a}\|_{C^0} + \|g\|_{C^1} \left(\sum_{p=1}^{k+1} |z'_p(\lambda_1; \lambda_2) - \bar{z}'_p(\lambda_1; \lambda_2)| \right) \right), \\ |F'_p(\lambda_2) - \bar{F}'_p(\lambda_2)| &\leq C_{\varepsilon_0, k} \left((\|f^{(1)}\|_{C^{1,1}} + \|\bar{f}^{(1)}\|_{C^{1,1}}) (\|f^{(2)}\|_{C^{1,1}} + \|\bar{f}^{(2)}\|_{C^{1,1}}) \|a - \bar{a}\|_{C^0} \right. \\ &\quad + \|f^{(1)} - \bar{f}^{(1)}\|_{C^1} \|f^{(2)}\|_{C^1} + \|f^{(2)} - \bar{f}^{(2)}\|_{C^1} \|\bar{f}^{(1)}\|_{C^1} \\ &\quad \left. + \|f^{(1)}\|_{C^1} \|f^{(2)}\|_{C^1} \left(\sum_{p=1}^{k+1} |z'_p(\lambda_1; \lambda_2) - \bar{z}'_p(\lambda_1; \lambda_2)| \right) \right). \end{aligned}$$

Therefore, we can get

$$\begin{aligned} \|h(t_p(\lambda_1; \lambda_2)) - \bar{h}(\bar{t}_p(\lambda_1; \lambda_2))\|_{C^1} &\leq C_{A, k, \varepsilon_0} \left((\|\varphi\|_{C^{1,1}} + \|\psi\|_{C^1} + \|g\|_{C^{1,1}} + \|\bar{g}\|_{C^{1,1}}) \|a - \bar{a}\|_{C^1} \right. \\ &\quad + (\|f^{(1)}\|_{C^{1,1}} + \|\bar{f}^{(1)}\|_{C^{1,1}}) (\|f^{(2)}\|_{C^{1,1}} + \|\bar{f}^{(2)}\|_{C^{1,1}}) \|a - \bar{a}\|_{C^1} \\ &\quad + (\|f^{(1)}\|_{C^1} + \|f^{(2)}\|_{C^1} + \|\bar{f}^{(1)}\|_{C^1} + \|\bar{f}^{(2)}\|_{C^1}) (\|f^{(2)} - \bar{f}^{(2)}\|_{C^1} + \|f^{(1)} - \bar{f}^{(1)}\|_{C^1}) \\ &\quad \left. + \|g - \bar{g}\|_{C^1} \right). \end{aligned}$$

For $H[\hat{n}]$, from (2.33)-(2.36), we know that

$$\begin{aligned} |H^+(t_p(0; x)) - \bar{H}^+(\bar{t}_p(0; x))| &\leq C \|h(t_p(\lambda_1; \lambda_2)) - \bar{h}(\bar{t}_p(\lambda_1; \lambda_2))\|_{C^1}, \\ \left| \frac{d}{dx} H^+(t_p(0; x)) - \frac{d}{dx} \bar{H}^+(\bar{t}_p(0; x)) \right| &\leq C \|h(t_p(\lambda_1; \lambda_2)) - \bar{h}(\bar{t}_p(\lambda_1; \lambda_2))\|_{C^1}. \end{aligned}$$

Thereby

$$|H^{+'}(t_p(0; x)) - \bar{H}^{+'}(\bar{t}_p(0; x))| \leq C_{\varepsilon_0, k} (\|h(t_p(\lambda_1; \lambda_2)) - \bar{h}(\bar{t}_p(\lambda_1; \lambda_2))\|_{C^1} + \|h\|_{C^1} \|a - \bar{a}\|_{C^1}).$$

For $H[n]$, from (2.32), we know that

$$\begin{aligned} |H(t_p(0; x)) - \bar{H}(\bar{t}_p(0; x))| &\leq C_{\varepsilon_0, k, A} \left(\|\tilde{u} - \tilde{v}\|_{C^0} + \|H[\hat{n}](t_p(0; x)) - \bar{H}[\hat{n}](\bar{t}_p(0; x))\|_{C^0} \right. \\ &\quad \left. + \|G(t_p(0; x)) - \bar{G}(\bar{t}_p(0; x))\|_{C^0} + \|F(t_p(0; x)) - \bar{F}(\bar{t}_p(0; x))\|_{C^0} \right). \end{aligned}$$

and

$$\begin{aligned} \left| \frac{d}{dx} H(t_p(0; x)) - \frac{d}{dx} \bar{H}(\bar{t}_p(0; x)) \right| &\leq C_{\varepsilon_0, k, A} \left(\|\tilde{u} - \tilde{v}\|_{C^1} \right. \\ &\quad \left. + \|H[\hat{n}](t_p(0; x)) - \bar{H}[\hat{n}](\bar{t}_p(0; x))\|_{C^1} \right. \\ &\quad \left. + \|G(t_p(0; x)) - \bar{G}(\bar{t}_p(0; x))\|_{C^1} \right. \\ &\quad \left. + \|F(t_p(0; x)) - \bar{F}(\bar{t}_p(0; x))\|_{C^1} \right). \end{aligned}$$

Thereby

$$\begin{aligned} |H'(t_p(0; x)) - \bar{H}'(\bar{t}_p(0; x))| &\leq C_{\varepsilon_0, k, A} \left(\|h\|_{C^1} \|a - \bar{a}\|_{C^1} + \|\tilde{u} - \tilde{v}\|_{C^1} \right. \\ &\quad \left. + \|H[\hat{n}](t_p(0; x)) - \bar{H}[\hat{n}](\bar{t}_p(0; x))\|_{C^1} \right. \\ &\quad \left. + \|G(t_p(0; x)) - \bar{G}(\bar{t}_p(0; x))\|_{C^1} \right. \\ &\quad \left. + \|F(t_p(0; x)) - \bar{F}(\bar{t}_p(0; x))\|_{C^1} \right). \end{aligned}$$

Therefore, we can get

$$\begin{aligned} \|H(t_p(0; x)) - \bar{H}(\bar{t}_p(0; x))\|_{C^1} &\leq C_{\varepsilon_0, k, A} \left((\|\varphi\|_{C^{1,1}} + \|\psi\|_{C^1} + \|g\|_{C^{1,1}} + \|\bar{g}\|_{C^{1,1}}) \|a - \bar{a}\|_{C^1} \right. \\ &\quad + (\|f^{(1)}\|_{C^{1,1}} + \|\bar{f}^{(1)}\|_{C^{1,1}}) (\|f^{(2)}\|_{C^{1,1}} + \|\bar{f}^{(2)}\|_{C^{1,1}}) \|a - \bar{a}\|_{C^1} \\ &\quad + (\|f^{(1)}\|_{C^1} + \|f^{(2)}\|_{C^1} + \|\bar{f}^{(1)}\|_{C^1} + \|\bar{f}^{(2)}\|_{C^1}) (\|f^{(2)} - \bar{f}^{(2)}\|_{C^1} + \|f^{(1)} - \bar{f}^{(1)}\|_{C^1}) \\ &\quad \left. + \|g - \bar{g}\|_{C^1} \right). \end{aligned}$$

For any $t \in [0, T]$, there exists some p and $x \in [0, L]$ such that $t = t_p(0; x)$. Therefore, we can get

$$\|H - \bar{H}\|_{C^1} \leq \|H(t_p(0; x)) - \bar{H}(\bar{t}_p(0; x))\|_{C^1} + \|H\|_{C^{1,1}} |t_p(0; x) - \bar{t}_p(0; x)|.$$

Thereby

$$\begin{aligned} \|H - \bar{H}\|_{C^1} &\leq C_{\varepsilon_0, k, A} \left((\|\varphi\|_{C^{1,1}} + \|\psi\|_{C^1} + \|g\|_{C^{1,1}} + \|\bar{g}\|_{C^{1,1}}) \|a - \bar{a}\|_{C^1} \right. \\ &\quad + (\|f^{(1)}\|_{C^{1,1}} + \|\bar{f}^{(1)}\|_{C^{1,1}}) (\|f^{(2)}\|_{C^{1,1}} + \|\bar{f}^{(2)}\|_{C^{1,1}}) \|a - \bar{a}\|_{C^1} \\ &\quad + (\|f^{(1)}\|_{C^1} + \|f^{(2)}\|_{C^1} + \|\bar{f}^{(1)}\|_{C^1} + \|\bar{f}^{(2)}\|_{C^1}) (\|f^{(2)} - \bar{f}^{(2)}\|_{C^1} + \|f^{(1)} - \bar{f}^{(1)}\|_{C^1}) \\ &\quad \left. + \|g - \bar{g}\|_{C^1} \right). \end{aligned}$$

For $\|u - v\|_{C^1}$, similar to the estimate of $\|\tilde{u} - \tilde{v}\|_{C^1}$, we can get

$$\begin{aligned} \|u - v\|_{C^1} &\leq C_{\varepsilon_0, k, A} \left((\|f^{(1)}\|_{C^1} + \|f^{(2)}\|_{C^1} + \|\bar{f}^{(1)}\|_{C^1} + \|\bar{f}^{(2)}\|_{C^1}) (\|f^{(2)} - \bar{f}^{(2)}\|_{C^1} + \|f^{(1)} - \bar{f}^{(1)}\|_{C^1}) \right. \\ &\quad + (\|\varphi\|_{C^{1,1}} + \|\psi\|_{C^{1,1}} + \|g\|_{C^{1,1}} + \|\bar{g}\|_{C^{1,1}} + (\|f^{(1)}\|_{C^{1,1}} + \|\bar{f}^{(1)}\|_{C^{1,1}}) (\|f^{(2)}\|_{C^{1,1}} + \|\bar{f}^{(2)}\|_{C^{1,1}})) \|a - \bar{a}\|_{C^1} \\ &\quad \left. + \|g - \bar{g}\|_{C^1} \right). \end{aligned}$$

3. ESTIMATION OF ITERATIVE SOLUTIONS FOR LINEARIZED EQUATIONS

In this section, we will show the proof of Proposition 1.1 with inductive reasoning. Denote $\tilde{a}^{(m)} = a^{(m)} - 1$, and we know that

$$\|\tilde{a}^{(m)}\|_{C^{1,1}} \leq C \|\tilde{U}^{(m)}\|_{C^{2,1}} \leq CC_P \varepsilon,$$

using the inductive assumption. Denote

$$\begin{aligned} G^{(m)} &= \left(\tilde{D}^+ \left(\tilde{U}^{(m)}, \tilde{U}_t^{(m)}, \tilde{U}_x^{(m)} \right) - \tilde{D}^+(0, 0, 0) \right) \tilde{D}^+(0, 0, 0)^{-1} \tilde{V}^{-(m)} \\ &\quad - \left(\tilde{D}^- \left(\tilde{U}^{(m)}, \tilde{U}_t^{(m)}, \tilde{U}_x^{(m)} \right) - \tilde{D}^-(0, 0, 0) \right) \tilde{D}^+(0, 0, 0)^{-1} \tilde{V}^{+(m)}. \end{aligned}$$

Then we have

$$\|G^{(m)}\|_{C^{1,1}} \leq C \|\tilde{U}^{(m)}\|_{C^{2,1}}^2 \leq CC_P^2 \varepsilon^2,$$

Denote

$$\begin{aligned} f^{(m,1)} &= \partial_x \tilde{U}^{(m)}, \\ f^{(m,2)} &= a^{(m)}. \end{aligned}$$

Then we have

$$\begin{aligned} \|f^{(m,1)}\|_{C^{1,1}} &\leq \|\tilde{U}^{(m)}\|_{C^{2,1}} \leq C_P \varepsilon, \\ \|f^{(m,2)}\|_{C^{1,1}} &\leq \|a^{(m)}\|_{C^{1,1}} \leq CC_P \varepsilon. \end{aligned}$$

Using (2.43) and (2.50), we can get

$$\begin{aligned} \|H^{(m+1)}\|_{C^{1,1}} &\leq 2C (1 + CC_P^2 \varepsilon) \varepsilon, \\ \|\tilde{V}^{(m+1)}\|_{C^{1,1}} &\leq 2C (1 + CC_P^2 \varepsilon) \varepsilon, \end{aligned}$$

and then

$$\|\tilde{U}^{(m+1)}\|_{C^{2,1}} \leq 2C (1 + CC_P^2 \varepsilon) \varepsilon.$$

Select ε_0 small enough and C_P large enough such that

$$2C (1 + CC_P^2 \varepsilon_0) \leq C_P.$$

Then we can get

$$\|H^{(m+1)}\|_{C^{1,1}} \leq C_P \varepsilon,$$

and

$$\|\tilde{U}^{(m+1)}\|_{C^{2,1}} \leq C_P \varepsilon.$$

Then we try to get the Cauchy property. Provided the method of obtaining the controls $h_i(t)$, we first consider the Cauchy property of $\tilde{\varphi}^{(m)}(x)$, where $\tilde{\varphi}^{(m)}(x) = \tilde{u}^{(m)}(T, x)$ and $\tilde{u}^{(m)}(t, x)$ is the solution of the equation below:

$$\begin{cases} \partial_t \tilde{u}^{\pm(m+1)} \pm a^{(m)} \partial_x \tilde{u}^{\pm(m+1)} = \mp \chi(t) \partial_x \tilde{U}^{(m)} (\partial_t \pm a^{(m)} \partial_x) (a^{(m)}), \\ x = L : \tilde{u}^{-(m+1)} = -\tilde{u}^{+(m+1)}, \quad t \in \mathbb{R}^+, \\ x = 0 : \tilde{u}^{-(m+1)} = A_0 \tilde{u}^{+(m+1)} + \tilde{H}(t) + \chi(t) G^{(m)}(t), \\ t = 0 : \tilde{u}^{(m+1)} = \varphi(x), \end{cases}$$

where $\chi(t)$ is the same as in Section 2 and $\tilde{H}(t)$ is a set of functions selected that satisfy the compatibility condition. Provided that $G^{(m)}(0)$ depends on $\varphi(x)$ and is independent of m , we can select the same set of functions $\tilde{H}(t)$ for all m . Using the inductive assumption, we can get

$$\begin{aligned} \|a^{(m)} - a^{(m-1)}\|_{C^1} &\leq C \left(\|\tilde{U}^{(m)} - \tilde{U}^{(m-1)}\|_{C^2} \right), \\ \|G^{(m)} - G^{(m-1)}\|_{C^1} &\leq C \left(\left(\|\tilde{U}^{(m)}\|_{C^2} + \|\tilde{U}^{(m-1)}\|_{C^2} \right) \|\tilde{U}^{(m)} - \tilde{U}^{(m-1)}\|_{C^2} \right), \\ \|f^{(m,1)} - f^{(m-1,1)}\|_{C^1} &\leq C \left(\|\tilde{U}^{(m)} - \tilde{U}^{(m-1)}\|_{C^2} \right), \end{aligned}$$

$$\left\| f^{(m,2)} - f^{(m-1,2)} \right\|_{C^1} \leq C \left(\left\| \tilde{U}^{(m)} - \tilde{U}^{(m-1)} \right\|_{C^2} \right).$$

Using (2.43) and (2.50), we can get

$$\left\| H^{(m+1)} - H^{(m)} \right\|_{C^1} \leq 2C^2\varepsilon (1 + 4CC_p + C_p\varepsilon + CC_p^2\varepsilon + 2C^2C_p^2\varepsilon) C_P\varepsilon\alpha^{m-1},$$

and then

$$\left\| \tilde{V}^{(m+1)} - \tilde{V}^{(m)} \right\|_{C^1} \leq 2C^2\varepsilon (1 + 4CC_p + C_p\varepsilon + CC_p^2\varepsilon + 2C^2C_p^2\varepsilon) C_P\varepsilon\alpha^{m-1},$$

and

$$\left\| \tilde{U}^{(m+1)} - \tilde{U}^{(m)} \right\|_{C^2} \leq 2C^2\varepsilon (1 + 4CC_p + C_p\varepsilon + CC_p^2\varepsilon + 2C^2C_p^2\varepsilon) C_P\varepsilon\alpha^{m-1}.$$

Select ε_0 small enough such that

$$2C^2\varepsilon_0 (1 + 4CC_p + C_p\varepsilon_0 + CC_p^2\varepsilon_0 + 2C^2C_p^2\varepsilon_0) < \alpha < 1.$$

The proof of Theorem 1.1 is completed.

APPENDIX A

This section is devoted to proving the following lemma, which is used to get the values and derivatives of the control functions $h_i(t)$ at $t_p(0;0)$, $t_p(0;L)$, $t_p(L;0)$ and $t_p(L;L)$, $i = 1, \dots, n$; $p = 1, \dots, k+1$.

Lemma A.1. *Consider the linear algebraic equations below:*

$$\psi = A^k BH_{k+1} + \dots + ABH_2 + BH_1, \quad (\text{A.1})$$

$$H_{2m-1}^- = H_{2m}^-, \quad 2m-1 \leq k, \quad (\text{A.2})$$

$$H_{2m+1}^+ = H_{2m}^+, \quad 2m \leq k, \quad (\text{A.3})$$

where $H_p = (H_p^-, H_p^+)^T$, $H_p^- \in \mathbb{R}^r$, $H_p^+ \in \mathbb{R}^s$. $\psi \in \mathbb{R}^n$. $H_p \in \mathbb{R}^n$, $p = 1, \dots, k+1$ are the unknowns to be solved.

$$A = \begin{pmatrix} & A_1 \\ A_2 & \end{pmatrix},$$

$$B = \begin{pmatrix} B_1 & \\ & B_2 \end{pmatrix} = \begin{pmatrix} I_{r_1} & & & \\ & O_{r_2} & & \\ & & I_{s_1} & \\ & & & O_{s_2} \end{pmatrix},$$

where $r_1 + r_2 = r$, $s_1 + s_2 = s$, $r + s = n$, $A_1 = (a_{ij})$, $i = 1, \dots, r$, $j = r+1, \dots, n$, $A_2 = (a_{ij})$, $i = r+1, \dots, n$, $j = 1, \dots, r$. If ψ satisfies the following condition

$$\psi_i = \sum_{j=1}^r a_{ij}\psi_j, \quad i = r+s_1+1, \dots, r+s, \quad (\text{A.4})$$

and the Kalman rank condition holds as follows,

$$\text{Rank} [B, A^k B, \dots, A^{k-1} B] = n, \quad (\text{A.5})$$

then there exists a set of solutions H_p , $p = 1, \dots, k+1$ of equation (A.1).

Proof. Without loss of generality, we can assume that k is odd. Denote

$$\bar{H}_i = \psi_i - \sum_{j=1}^r a_{ij}\psi_j, \quad i = r+1, \dots, r+s. \quad (\text{A.6})$$

Then we have

$$\psi^+ = A_2\psi^- + \bar{H}. \quad (\text{A.7})$$

From the condition (A.4), we know that the last s_2 components of \bar{H} are zero. The following is an attempt to write conditions (A.1)-(A.3) as a new linear algebraic equation. Then the equation (A.1) - (A.3) can be written as follows:

$$\begin{pmatrix} \psi^- \\ \psi^+ \\ 0 \\ 0 \\ \vdots \\ 0 \\ 0 \end{pmatrix} = \begin{pmatrix} O & A_1 \cdots A_2 A_1 B_2 & A_1 \cdots A_2 B_1 & O & \cdots & O & A_1 B_2 & I_r B_1 & O \\ A_2 \cdots A_1 A_2 B_1 & O & O & A_2 \cdots A_1 B_2 & \cdots & A_2 B_1 & O & O & I_s B_2 \\ I_r & O & -I_r & O & \cdots & O & O & O & O \\ O & O & O & I_s & \cdots & O & O & O & O \\ & & & & \cdots & & & & \\ & & & & \cdots & O & -I_s & O & O \\ & & & & \cdots & I_r & O & -I_r & O \end{pmatrix} \begin{pmatrix} H_{k+1}^- \\ H_{k+1}^+ \\ H_k^- \\ H_k^+ \\ \vdots \\ H_2^- \\ H_2^+ \\ H_1^- \\ H_1^+ \end{pmatrix}.$$

Multiply the third row of the above equation by $-A_2 \cdots A_1 A_2 B_1$ and add it to the first row, multiply the forth row of the above equation by $-A_2 \cdots A_1 B_2$ and add it to the second row and continue the process. Then the first two rows of the equation can be written as

$$\begin{pmatrix} \psi^- \\ \psi^+ \end{pmatrix} = \begin{pmatrix} O & A_1 A_2 \cdots A_1 B_2 & A_1 \cdots A_2 B_1 & O & \cdots & O & A_1 B_2 & I_r B_1 & O \\ O & O & A_2 A_1 \cdots A_2 B_1 & O & \cdots & O & A_2 A_1 B_2 & A_2 B_1 & I_s B_2 \end{pmatrix} \begin{pmatrix} H_{k+1}^- \\ H_{k+1}^+ \\ H_k^- \\ H_k^+ \\ \vdots \\ H_2^- \\ H_2^+ \\ H_1^- \\ H_1^+ \end{pmatrix}. \quad (\text{A.8})$$

Let $H_{k+1}^+ = 0$. Combined with (A.7), multiply the first row of the equation (A.8) by $-A_2$ and add it to the second row. Then we have

$$\begin{pmatrix} \psi^- \\ \bar{H} \end{pmatrix} = \begin{pmatrix} O & O & A_1 \cdots A_2 B_1 & O & \cdots & O & A_1 B_2 & I_r B_1 & O \\ O & O & O & O & \cdots & O & O & O & I_s B_2 \end{pmatrix} \begin{pmatrix} H_{k+1}^- \\ H_{k+1}^+ \\ H_k^- \\ H_k^+ \\ \vdots \\ H_2^- \\ H_2^+ \\ H_1^- \\ H_1^+ \end{pmatrix}. \quad (\text{A.9})$$

Notice that (A.5) can be written as

$$\text{Rank} \begin{pmatrix} A_1 \cdots A_2 B_1 & O & \cdots & O & A_1 B_2 & I_r B_1 & O \\ O & A_2 \cdots A_1 B_2 & \cdots & A_2 B_1 & O & O & I_s B_2 \end{pmatrix} = n, \quad (\text{A.10})$$

which implies that the first $r + s_1$ rows of the coefficient matrix of equation (A.8) are full rank. Therefore, Combined with the condition that the last s_2 components of \bar{H} are zero, we know that the rank of the equation augmented matrix is equal to the rank of the original coefficient matrix, and thus (A.9) has a solution. \square

Corollary A.2. Consider the linear algebraic equation (A.1) and

$$H_{2m-1}^+ = H_{2m}^+, \quad (\text{A.11})$$

$$H_{2m+1}^- = H_{2m}^-. \quad (\text{A.12})$$

Under the conditions (A.5), if ψ satisfies

$$\psi_i = \sum_{j=r+1}^{r+s} a_{ij} \psi_j, \quad i = r_1 + 1, \dots, r, \quad (\text{A.13})$$

then there exists a set of solutions H_p , $p = 1, \dots, k + 1$, of equation (A.1).

Proof. Define $\tilde{\psi}$ as $\tilde{\psi}^- = \psi^+$, $\tilde{\psi}^+ = \psi^-$, \tilde{A} as $\tilde{A}^1 = A^2$, $\tilde{A}^2 = A^1$, and \tilde{H}_p as $\tilde{H}_p^- = H_p^+$, $\tilde{H}_p^+ = H_p^-$, and then the proof is the same as the above lemma. \square

Remark A.3. *In the proof of Lemma A.1 one obtains $H_1^+ = \bar{H}$, and in the proof of Corollary A.2 one obtains $H_1^- = \bar{H}$.*

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