UNIQUE CONTINUATION AND TIME DECAY FOR A HIGHER-ORDER WATER WAVE MODEL

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Abstract. This work is devoted to prove the exponential decay for the energy of solutions of a higher order Korteweg–de Vries (KdV)–Benjamin–Bona–Mahony (BBM) equation on a periodic domain with a localized damping mechanism. Following the method in [L. Rosier and B.-Y. Zhang, J. Diff. Equ. 254 (2013) 141–178], which combines energy estimates, multipliers and compactness arguments, the problem is reduced to prove the Unique Continuation Property (UCP) for weak solutions of the model. Then, this is done by deriving Carleman estimates for a system of coupled elliptic-hyperbolic equations.

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1. Introduction

The field of dispersive equations has received increasing attention since the pioneering works of Stokes, Boussinesq and Korteweg and de Vries in the nineteenth century. It pertains to a modern line of research which is important both scientifically as well as for potential applications. On the one hand, the mathematical theoretical research of dispersive equations is important for applied sciences since it has provided solid foundations for the verification and applicability of these models. On the other hand, this theoretical research has proved to be very valuable for mathematics itself. Such equations have presented very difficult and interesting challenges, motivating the development of many new ideas and techniques within mathematical analysis. Particularly, sets of equations were derived to describe the dynamics of the waves in some specific physical regimes and much effort has been expended on various aspects of the initial and boundary value problems. In this context, Bona, Carvajal, Panthee and Scialom [2] derived and analyzed a higher order water wave model to describe the unidirectional propagation of water waves by using the second order approximation in the two-way model, the so-called abcd-system introduced in [3, 4]. The model is also known as the fifth order KdV–BBM type equation and has the form

\[ u_t + u_x - b_1 u_{txx} + a_1 u_{xxx} + b u_{xxxx} + a u_{xxxxx} + 3 \frac{u}{2} u_x + \gamma (u^2)_{xxx} - \frac{7}{48} (u_x^2)_x - \frac{1}{8} (u^3)_x = 0. \] (1.1)

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The unknown $u$ is a real valued function of the real variables $x$ and $t$ and subscripts indicate partial differentiation. The five parameters $a, a_1, b, b_1$ and $\gamma$ are not arbitrary. Indeed, they are determined by the choice of five more fundamental parameters $\theta, \lambda, \mu, \lambda_1$ and $\mu_1$. The constant $\theta$ has physical significance. It is related to the height at which the horizontal velocity is specified, a dependent variable which does not appear explicitly in these unidirectional models. The parameter $\theta \in [0, 1]$ because the vertical coordinate has been scaled by the undisturbed depth $h_0$. The constants $\lambda, \mu, \lambda_1$ and $\mu_1$ are modelling parameters and, in principle, can take any real value. However, the five parameters that appear in (1.1) are not independent and should satisfy some relations. All of them are shown in [2]. Such conditions come from the physics of the problem and we tacitly assume them to hold throughout the entire paper. Depending on the problem under study (well-posedness of the relations), additional restrictions on the sign of these parameters will be imposed later on.

The incorporation of damping mechanisms is often crucial in obtaining good agreement between experimental observations and the prediction of theoretical models describing the propagation of waves in dispersive media. The problem might be easy to solve when the underlying models have a strong intrinsic dissipative nature, but very often, as the cases we address here, the models are of conservative nature and the decay requires appropriate damping mechanisms. Obviously, for practical purposes, it is desirable to achieve this property with a minimal amount of damping both in what concerns its support and its intensity.

In this work, considerations will be given for model (1.1) on the one-dimensional torus $\mathbb{T} = \mathbb{R}/(2\pi\mathbb{Z})$, with a localized damping term. Our purpose is to investigate the dissipative effects generated by this damping when $t \to \infty$. Our analysis does not depend on particular relations between the coefficients of the system. However, in order to provide the tools needed to deal with the problem, we assume that

$$b, \ b_1 > 0.$$  

Under the above conditions, the following closed-loop system will be considered:

$$u_t + u_x - b_1 u_{xxx} + a_1 u_{xxxx} + bu_{xxxxx} + au_{xxxxx}$$
$$+ \frac{3}{2} tu_x + \gamma (u^2)_{xxx} - \frac{7}{48} (u^2)_x - \frac{1}{8} (u^3)_x = \sigma(1 - b_1 \partial_x^2 + b \partial_x^4)[\sigma u], \quad (x, t) \in \mathbb{T} \times (0,T)$$
$$u(x,0) = u_0(x), \quad x \in \mathbb{T},$$

where $\sigma \in C^\infty(\mathbb{T})$ is a nonzero function. We also introduce the set

$$\omega = \{ x \in \mathbb{T} : \sigma(x) \neq 0 \} \neq \emptyset.$$  

Then, if we consider the following equivalent norm in the $L^2$-based Sobolev space $H^2(\mathbb{T})$,

$$\|u(\cdot, t)\|^2_{H^2(\mathbb{T})} = \int_T (u^2 + b_1 u_x^2 + b u_{xx}^2) \, dx,$$  

at least formally, we can deduce that

$$\|u(\cdot, t)\|^2_{H^2(\mathbb{T})} - \|u_0\|^2_{H^2(\mathbb{T})} = -2 \int_0^t \|\sigma u(s)\|^2_{H^2(\mathbb{T})} \, ds.$$  

Indeed, to obtain the identity above we multiply the equation in (1.2) by $u$ and integrate by parts over the spatial domain $\mathbb{T}$. Identity (1.5) shows that the term on the right hand side plays the role of a damping mechanism. Moreover, it indicates that the $H^2$-norm decreases along the trajectories of the system, which generates a flow that can be continued indefinitely in the temporal variable. Therefore, we can ask whether the solutions converge to zero, as $t \to \infty$, and at which rate they decay.
In view of (1.5), the problem of the exponential decay can be stated in the following equivalent form: To find $T > 0$ and $C > 0$, such that

$$\|u_0\|_{H^2(T)}^2 \leq C \int_0^T \|\sigma u(t)\|_{H^2(T)}^2 dt \quad (1.6)$$

holds for every finite energy solution of (1.2). Indeed, from (1.6) and (1.5), we have that $E(T) \leq \beta E(0)$ with $0 < \beta < 1$, which combined with the semigroup property, allows us to derive the exponential decay of the $H^2$-norm of the solutions.

This paper is devoted to analyze this problem. Our analysis was inspired by the results proved in [11] from which we borrow the main ideas involved in our proofs. In fact, proceeding as in [11], which combine multipliers, energy estimates and compactness arguments, the problem of obtaining (1.6) is reduced to show that the unique solution of (1.2), such that $\sigma(x)u = 0$ everywhere, has to be the trivial one. To solve this problem we develop a Carleman inequality for weak solutions of the model as it has been done in [11] for a KdV–BBM equation. The equation is first split into a coupled system of an elliptic equation and a transport equation. Next, some Carleman estimates are derived with the same singular weights for both the elliptic and the hyperbolic equations. Finally, the unique continuation result is proved by combining these Carleman estimates with a regularization process. However, this unique continuation result cannot be applied directly due to the regularity of solutions we are dealing with. Therefore, some additional assumptions concerning the initial conditions are needed. More precisely, we assume that $0 < r \leq \|u_0\|_{H^2(T)}$ and $\|u_0\|_{H^3(T)} \leq R$, for given $r, R > 0$. These conditions seem to be technical, but, in their absence, we do not know how to derive the result. It is also important to emphasize that the choice of the damping function was motivated by the controllability results obtained in [1] for corresponding linearized system. Indeed, as an application of the controllability result, we construct feedback controls via some results obtained in [8, 12], such that the resulting linearized closed-loop system is shown to be exponentially stable. Such stabilization results play a crucial role in the analysis we describe above.

We remark that the unique continuation property for the BBM equation is still an open problem. Moreover, since the underlying Cauchy problem is a characteristic one, we cannot expect to apply Carleman-type estimates or the classical Holmgren uniqueness theorem. In (1.1), the presence of the higher-order KdV term $u_{xxxxx}$ results in much better properties and allows to establish a unique continuation result.

It is also worth mentioning that, in addition to the analysis carried out in the work, the stabilization of the KdV and BBM equations have also been studied considering other types of damping mechanisms. In this sense, we refer to [10, 11] for a quite complete review of the field.

The remainder of this paper is organized as follows: in Section 2, we prove some Carleman estimates and derive a unique continuation property for the higher-order KdV–BBM equation. Section 3 is devoted to the stabilization of the damped equation. Finally, for the sake of completeness, we include in the Appendix some computations used in Section 3 and the proof a Carleman estimate derived in [11].

2. Carleman estimates

The first part of this section is devoted to prove an appropriate Carleman estimate for the higher-order KdV–BBM equation

$$u_t + u_x - b_1 u_{tx} + a_1 u_{xxx} + b u_{txxx} + a u_{xxxx} + \frac{3}{2} uu_x + \gamma u^{2}_{xxx} - \frac{7}{48} u^2_x - \frac{1}{8} u^3_x = 0, \quad (x, t) \in \mathbb{T} \times (0, T), \quad (2.1)$$
or

\[ u_t - b_1u_{xxx} + bu_{xxxx} + au_{xxxxx} + q(u)u_x + p(u)u_{xxx} + r(u)u_{xx} = 0, \quad (x, t) \in \mathbb{T} \times (0, T), \]  

(2.2)

where \( q(u) = 1 + \frac{3}{2}u - \frac{3}{2}u^2, \) \( p(u) = a_1 + 2\gamma u \) and \( r(u) = (6\gamma - \frac{7}{2\pi})u_x. \)

Next, this Carleman estimate is employed to prove the following unique continuation result:

**Theorem 2.1.** Let \( a, b \neq 0, \) \( T > \frac{2\pi b}{|a|} \) and \( q, p, r \in L^\infty(0, T; L^\infty(\mathbb{T})). \) Let \( \omega \subset \mathbb{T} \) be a nonempty open set. Let \( u \in L^2(0, T; H^4(\mathbb{T})) \cup L^\infty(0, T; H^3(\mathbb{T})) \) satisfy (2.2) and

\[ u(x, t) = 0 \quad \text{for a.e.} \quad (x, t) \in \omega \times (0, T). \]  

(2.3)

Then, \( u \equiv 0 \) in \( \mathbb{T} \times (0, T). \)

**Proof.** We first assume that

\[ u \in L^2(0, T; H^4(\mathbb{T})). \]  

(2.4)

and let \( w = u - b_1u_{xx} + bu_{xxxx} \in L^2(0, T; L^2(\mathbb{T})). \) Then, the pair \((u, w)\) solves the following system

\[ u - b_1u_{xx} + bu_{xxxx} = w \]  

(2.5)

\[ w_t + \frac{a}{b} w_x = \left( \frac{a}{b} - q \right)u_x - \left( \frac{ab_1}{b} + p \right)u_{xxx} - ru_{xx}. \]  

(2.6)

Just to make the assumption of the theorem clear, we recall the following remark, which can be found in [11]:

**Remark 2.2.** There is a finite speed propagation for KdV–BBM. For instance, if we assume that \( q(x) = \frac{a}{b}, \) \( p(x) = -\frac{ab_1}{b} \) and \( r(x) = 0 \) for all \( x \in \mathbb{T}, \) where \( a, b, b_1 > 0 \) are given, and that \( \omega = (2\pi - \epsilon, 2\pi) \) for a small \( \epsilon > 0, \) then the UCP fails in time \( T \leq \frac{b(2\pi - 2\epsilon)}{a}. \) Indeed, picking any nontrivial initial state \( u_0 \in C_0^\infty(0, \epsilon), \) we easily see that the solution \((u, w)\) of (2.5)–(2.6) is \( u(x, t) = u_0(x - \frac{a}{b}t), \) \( w(x, t) = w_0(x - \frac{a}{b}t), \) where \( w_0 = (I - \partial^2_x)u_0. \) Then, \( u(x, t) = 0 \) for \( (x, t) \in \omega \times \left(0, \frac{b(2\pi - 2\epsilon)}{a}\right) \) although \( u \neq 0. \) Hence, the condition \( T > \frac{2\pi \epsilon}{|a|} \) in the Theorem 2.1 is sharp.

We choose a system of coordinates and indentify \( \mathbb{T} \) with \( [0, 2\pi). \) Thus, without loss of generality, we can assume that \( a > 0, \) and that \( \omega = (2\pi - \eta, 2\pi + \eta) \sim (0, \eta) \cup (2\pi - \eta, 2\pi) \) for some \( \eta \in (0, \pi) \) (choosing the origin of the coordinates inside \( \omega \)). Then, we consider \( T, \) such that

\[ T > \frac{2b\pi}{a}. \]  

(2.7)

Following the approach developed in [11], we first obtain some Carleman estimates for the elliptic equation (2.5) and the transport equation (2.6) with the same weights function. Next, we combine them to derive a single one for (2.2). In order to do that, we pick \( \delta > 0 \) and \( \rho \in (0, 1), \) such that

\[ \frac{\rho a}{b} T > 2\pi + \delta \]  

(2.8)

and a function \( \psi \in C^\infty([0, 2\pi]) \) satisfying

\[ \psi(x) = (x + \delta)^2 \quad \text{for} \quad x \in \left[ \frac{\eta}{2}, 2\pi - \frac{\eta}{2} \right], \]  

(2.9)
\[
\frac{d^k \psi}{dx^k}(0) = \frac{d^k \psi}{dx^k}(2\pi) \quad \text{for } k = 1, 2, 3, 4, 5, 6, 7, \quad (2.10) \\
2\delta \leq \frac{d \psi}{dx}(x) \leq 2(2\pi + \delta) \quad \text{for } x \in [0, 2\pi]. \quad (2.11)
\]

Then, we introduce the function \( \varphi \in C^\infty([0, 2\pi] \times \mathbb{R}) \) as follows
\[
\varphi(x, t) = \psi(x) - \rho a^2 t^2. \quad (2.12)
\]

Under the above considerations, we derive the following Carleman estimate for (2.2).

**Proposition 2.3.** Let \( \omega, \ a \) and \( T \) be as above. Then, there exist some positive numbers \( s_2 \) and \( C_2 \), such that, for all \( s \geq s_2 \) and all \( u \in L^2(0, T; H^4(\mathbb{T})) \) satisfying (2.2), we have
\[
\int_0^T \int_T s|u_{xxxx}|^2 + s|u_{xx}|^2 + s^3|u_{xx}|^2 + s^5|u_x|^2 + s^7|u|^2 e^{2s\varphi} \, dx \, dt \\
+ s \int_T |u - b_1 u_{xx} + bu_{xxxx}|^2 e^{2s\varphi} \big|_{t=0} \, dx \\
\leq C_2 \int_0^T \int_\omega s|u_{xxxx}|^2 + s^3|u_{xx}|^2 + s^7|u|^2 e^{2s\varphi} \, dx \, dt. 
\]

**Proof.** In order to make the reading easier, we proceed in several steps.

- Carleman estimate for the transport equation.

**Lemma 2.4.** There exist \( s_1 \geq s_0 \) and \( C_1 > 0 \) such that for all \( s \geq s_1 \) and all \( w \in L^2(\mathbb{T} \times (0, T)) \) with \( w_t + \frac{a}{b} w_x \in L^2(\mathbb{T} \times (0, T)) \), the following holds
\[
\int_0^T \int_\mathbb{T} |w|^2 e^{2s\varphi} \, dx \, dt + \int_\mathbb{T} s|w|^2 e^{2s\varphi} \big|_{t=0} \, dx + \int_\mathbb{T} s|w|^2 e^{2s\varphi} \big|_{t=T} \, dx \\
\leq C_1 \left( \int_0^T \int_\mathbb{T} |w_t + \frac{a}{b} w_x|^2 e^{2s\varphi} \, dx \, dt + \int_0^T \int_\omega |w|^2 e^{2s\varphi} \, dx \, dt \right). \quad (2.14)
\]

**Proof.** The result was proved in Lemma 5.5 of [11]. For the sake of completeness we have included the proof in the Appendix.

- Carleman estimate for the elliptic equation.

**Lemma 2.5.** There exist \( s_0 \geq 1 \) and \( C_0 > 0 \), such that, for all \( s \geq s_0 \) and all \( u \in H^4(\mathbb{T}) \), the following holds
\[
\int_\mathbb{T} |s|u_{xxxx}|^2 + s^3|u_{xx}|^2 + s^5|u_x|^2 + s^7|u|^2 e^{2s\varphi} \, dx \\
\leq C_0 \left( \int_\mathbb{T} |u_{xxxx}|^2 e^{2s\varphi} \, dx + \int_\omega (s^7|u|^2 + s^3|u_{xx}|^2) e^{2s\varphi} \, dx \right). \quad (2.15)
\]

**Proof.** We start by considering a classical change of function and an appropriate differential operator. More precisely, let \( v = e^{s\varphi} u \) and \( P = \partial_x^4 \). Then, we decompose \( e^{s\varphi} Pu \) as follows
\[
e^{s\varphi} Pu = e^{s\varphi} P(e^{-s\varphi} v) = P_p v + P_n v,
\]
where

\[ P_p v = (s^4 \psi_x^4 + 3s^2 \psi_x^2 + 4s^2 \psi_{xxx} \psi_x) v + 12s^2 \psi_x \psi_{xx} v_x + 6s^2 \psi^2_{xx} v_x + v_{xxxx}, \]  
(2.16)

\[ P_n v = -(6s^3 \psi_x^2 \psi_{xx} + s \psi_{xxxx}) v - (4s^3 \psi_x^3 + 4s \psi_{xxx}) v_x - 6s \psi_x v_{xx} - 4s \psi v_{xxx}. \]  
(2.17)

From the above decomposition, we obtain

\[ \| e^\psi Pu \|^2 = \| P_p v \|^2 + \| P_n v \|^2 + 2(P_p v, P_n v), \]

where \((f, g) = \int_T fg dx\), and \(\| f \| = (f, f)\).

The next steps are devoted to analyze the inner product in the identity above. First, observe that, (2.16) and (2.17) lead to

\[
(P_p v, P_n v) = ((s^4 \psi_x^4 + 3s^2 \psi_x^2 + 4s^2 \psi_{xxx} \psi_x) v, -(6s^3 \psi_x^2 \psi_{xx} + s \psi_{xxxx}) v) \\
+ ((s^4 \psi_x^4 + 3s^2 \psi_x^2 + 4s^2 \psi_{xxx} \psi_x) v, -(4s^3 \psi_x^3 + 4s \psi_{xxx}) v_x) \\
+ ((s^4 \psi_x^4 + 3s^2 \psi_x^2 + 4s^2 \psi_{xxx} \psi_x) v_x, -6s \psi_x v_{xx}) \\
+ (6s^2 \psi_x^2 \psi_{xx} v_{xx}, -(4s^3 \psi_x^3 + 4s \psi_{xxx}) v_x) + (12s^2 \psi_x \psi_{xx} v_x, -(6s^3 \psi_x^2 \psi_{xx} + s \psi_{xxxx}) v) \\
+ (12s^2 \psi_x v_{xx} v_x, -(4s^3 \psi_x^3 + 4s \psi_{xxx}) v) + (v_{xxxx}, -(4s^3 \psi_x^3 + 4s \psi_{xxx}) v_x) \\
+ (v_{xxxx}, 6s \psi_x v_{xx}) \\
+ \frac{16}{\sum I_n}.
\]

Next, we compute each term \(I_n\). This is done by employing (2.10) and by the integration by parts in \(x\):

\[
I_1 = -\int_T (s^4 \psi_x^4 + 3s^2 \psi_x^2 + 4s^2 \psi_{xxx} \psi_x)(6s^3 \psi_x^2 \psi_{xx} + s \psi_{xxxx}) v^2 dx
\]

\[
I_2 = -\int_T (s^4 \psi_x^4 + 3s^2 \psi_x^2 + 4s^2 \psi_{xxx} \psi_x)(4s^3 \psi_x^3 + 4s \psi_{xxx}) v_x v dx
\]

\[
= \int_T [(s^4 \psi_x^4 + 3s^2 \psi_x^2 + 4s^2 \psi_{xxx} \psi_x)(2s^3 \psi_x^3 + 2s \psi_{xxx})] v^2 dx
\]

\[
I_3 = -\int_T (s^4 \psi_x^4 + 3s^2 \psi_x^2 + 4s^2 \psi_{xxx} \psi_x)(6s \psi_x v_{xx}) v v_{xx} dx
\]

\[
= \int_T [(s^4 \psi_x^4 + 3s^2 \psi_x^2 + 4s^2 \psi_{xxx} \psi_x)(6s \psi_x v_{xx})] v v_{xx} dx
\]

\[
+ \int_T [(s^4 \psi_x^4 + 3s^2 \psi_x^2 + 4s^2 \psi_{xxx} \psi_x)(6s \psi_x)] v^2_{xx} dx
\]

\[
= -\int_T [(s^4 \psi_x^4 + 3s^2 \psi_x^2 + 4s^2 \psi_{xxx} \psi_x)(3s \psi_{xx})] v^2_{xx} dx
\]

\[
+ \int_T [(s^4 \psi_x^4 + 3s^2 \psi_x^2 + 4s^2 \psi_{xxx} \psi_x)(6s \psi_x)] v^2_{xx} dx
\]
\[ I_4 = -\int_T (s^4 \psi_x^4 + 3s^2 \psi_{xx}^2 + 4s^2 \psi_{xxx} \psi_x) 4s \psi_x v v_{xxx} dx \]
\[ = \int_T [(s^4 \psi_x^4 + 3s^2 \psi_{xx}^2 + 4s^2 \psi_{xxx} \psi_x) 4s \psi_x]_x v v_{xx} dx \]
\[ + \int_T (s^4 \psi_x^4 + 3s^2 \psi_{xx}^2 + 4s^2 \psi_{xxx} \psi_x) 4s \psi_x v_x v_{xx} dx \]
\[ = - \int_T [(s^4 \psi_x^4 + 3s^2 \psi_{xx}^2 + 4s^2 \psi_{xxx} \psi_x) 4s \psi_x]_x v_x^2 dx \]
\[ - \int_T [(s^4 \psi_x^4 + 3s^2 \psi_{xx}^2 + 4s^2 \psi_{xxx} \psi_x) 4s \psi_x]_x v_x^2 dx \]
\[ + \int_T (s^4 \psi_x^4 + 3s^2 \psi_{xx}^2 + 4s^2 \psi_{xxx} \psi_x) 2s \psi_x x v_x^2 dx \]
\[ = \int_T [(s^4 \psi_x^4 + 3s^2 \psi_{xx}^2 + 4s^2 \psi_{xxx} \psi_x) 2s \psi_x]_{xxx} v_x^2 dx \]
\[ - \int_T [(s^4 \psi_x^4 + 3s^2 \psi_{xx}^2 + 4s^2 \psi_{xxx} \psi_x) 6s \psi_x]_x v_x^2 dx \]
\[ I_5 = -\int_T 12s^2 \psi_x \psi_{xx} (6s^3 \psi_x^2 \psi_{xx} + s \psi_{xxxx}) v v_x dx \]
\[ = \int_T [6s^2 \psi_x \psi_{xx} (6s^3 \psi_x^2 \psi_{xx} + s \psi_{xxxx})]_x v_x^2 dx \]
\[ I_6 = -\int_T 12s^2 \psi_x \psi_{xx} (4s^3 \psi_x^3 + 4s \psi_{xxx}) v_x^2 dx \]
\[ I_7 = -\int_T 12s^2 \psi_x \psi_{xx} 6s \psi_{xx} v_x v_{xx} dx = \int_T [36s^3 \psi_x \psi_{xx}^2]_x v_x^2 dx \]
\[ I_8 = -\int_T 12s^2 \psi_x \psi_{xx} 4s \psi_x v_x v_{xxx} dx = -\int_T 48s^3 \psi_x \psi_{xx} v_x v_{xx} dx \]
\[ = \int_T [48s^3 \psi_x \psi_{xx}]_x v_x v_{xx} dx + \int_T [48s^3 \psi_x \psi_{xx} v_x^2 v_{xx}]_x dx \]
\[ = -\int_T [24s^3 \psi_x \psi_{xx}]_{xxx} v_x^2 dx + \int_T [48s^3 \psi_x \psi_{xx} v_x^2 v_x]_x dx \]
\[ I_9 = -\int_T 6s^2 \psi_x^2 (6s^3 \psi_x^2 \psi_{xx} + s \psi_{xxxx}) v v_x dx \]
\[ = \int_T [6s^2 \psi_x^2 (6s^3 \psi_x^2 \psi_{xx} + s \psi_{xxxx})]_x v v_x dx + \int_T 6s^2 \psi_x^2 (6s^3 \psi_x^2 \psi_{xx} + s \psi_{xxxx}) v_x^2 dx \]
\[ = -\int_T [3s^2 \psi_x^2 (6s^3 \psi_x^2 \psi_{xx} + s \psi_{xxxx})]_{xxx} v_x^2 dx + \int_T 6s^2 \psi_x^2 (6s^3 \psi_x^2 \psi_{xx} + s \psi_{xxxx}) v_x^2 dx \]
\[ I_{10} = -\int_T 6s^2 \psi_x^2 (4s^3 \psi_x^3 + 4s \psi_{xxx}) v_x v_{xx} dx = \int_T [3s^2 \psi_x^2 (4s^3 \psi_x^3 + 4s \psi_{xxx})]_x v_x^2 dx \]
\[ I_{11} = -\int_T 6s^2 \psi_x^2 6s \psi_{xx} v_x^2 dx = -\int_T 36s^3 \psi_x \psi_{xx} v_x^2 dx \]
\[ I_{12} = -\int_T 6s^2 \psi_x^2 4s \psi_{xx} v_x v_{xx} dx = \int_T [12s^3 \psi_x^3]_x v_x^2 \]
\[ I_{13} = -\int_T (6s^3 \psi_x^2 \psi_{xx} + s \psi_{xxxx}) v v_{xxxx} dx = \int_T [6s^3 \psi_x^2 \psi_{xx} + s \psi_{xxxx}]_x v v_{xx} dx \]
By combining the identities above, we get

\[
\begin{align*}
&+ \int_T (6s^3 \psi_x^2 \psi_{xx} + s \psi_{xxxx}) v_x v_{xxx} dx \\
&= -\int_T [6s^3 \psi_x^2 \psi_{xx} + s \psi_{xxxx}] v_x v_{xx} dx - \int_T [6s^3 \psi_x^2 \psi_{xx} + s \psi_{xxxx}] v_x v_{xx} dx \\
&- \int_T [6s^3 \psi_x^2 \psi_{xx} + s \psi_{xxxx}] v_x v_{xx} dx - \int_T [6s^3 \psi_x^2 \psi_{xx} + s \psi_{xxxx}] v_x v_{xx} dx \\
&= \int_T [6s^3 \psi_x^2 \psi_{xx} + s \psi_{xxxx}] v_x v_{xx} dx + \int_T [6s^3 \psi_x^2 \psi_{xx} + s \psi_{xxxx}] v_x v_{xx} dx \\
&+ \int_T [6s^3 \psi_x^2 \psi_{xx} + s \psi_{xxxx}] v_x v_{xx} dx - \int_T [6s^3 \psi_x^2 \psi_{xx} + s \psi_{xxxx}] v_x v_{xx} dx \\
&= -\int_T \frac{1}{2} [6s^3 \psi_x^2 \psi_{xx} + s \psi_{xxxx}] v_x v_{xx} dx + \int_T 2(6s^3 \psi_x^2 \psi_{xx} + s \psi_{xxxx}) v_x v_{xx} dx \\
&- \int_T (6s^3 \psi_x^2 \psi_{xx} + s \psi_{xxxx}) v_x^2 dx \\
I_{14} &= -\int_T (4s^3 \psi_x^3 + 4s \psi_{xxx}) v_x v_{xxxx} dx = \int_T [(4s^3 \psi_x^3 + 4s \psi_{xxx}) v_x v_{xxxx} dx \\
&+ \int_T (4s^3 \psi_x^3 + 4s \psi_{xxx}) v_x v_{xxxx} dx \\
&= -\int_T [(4s^3 \psi_x^3 + 4s \psi_{xxx}) v_x v_{xxxx} dx - \int_T [(4s^3 \psi_x^3 + 4s \psi_{xxx}) v_x v_{xxxx} dx \\
&- \int_T [(2s^3 \psi_x^3 + 2s \psi_{xxx}) v_x v_{xx} dx \\
&= \int_T [(2s^3 \psi_x^3 + 2s \psi_{xxx}) v_x v_{xx} dx - \int_T 3(2s^3 \psi_x^3 + 2s \psi_{xxx}) v_x v_{xx} dx \\
I_{15} &= -\int_T 6s \psi_{xxx} v_x v_{xxxx} dx = \int_T 6s \psi_{xxx} v_x v_{xxxx} dx + \int_T 6s \psi_{xxx} v_x v_{xxxx} dx \\
&= -\int_T 3s \psi_{xxx} v_{xx} dx + \int_T 6s \psi_{xxx} v_{xx} dx \\
I_{16} &= -\int_T 4s \psi_x v_{xxx} v_{xxxx} dx = \int_T 2s \psi_x v_{xx} dx.
\end{align*}
\]

By combining the identities above, we get

\[
\|
\begin{align*}
&= \|P_p v\|^2 + \|P_n v\|^2 + 2 \int_T h_1(\psi) v^2 dx + 2 \int_T h_2(\psi) v^2 dx + \\
&2 \int_T h_3(\psi) v_{xx}^2 dx + 2 \int_T h_4(\psi) v_{xxx}^2 dx,
\end{align*}
\]

where

\[
\begin{align*}
h_1(\psi) &= [(s^4 \psi_x^4 + 3s^3 \psi_x^2 + 4s^2 \psi_{xxx} \psi_x)(2s^3 \psi_x^3 + 2s \psi_{xxx})], \\
&= (s^4 \psi_x^4 + 3s^3 \psi_x^2 + 4s^2 \psi_{xxx} \psi_x)(6s^3 \psi_x^2 \psi_{xx} + s \psi_{xxxx}) \\
&= [(s^4 \psi_x^4 + 3s^3 \psi_x^2 + 4s^2 \psi_{xxx} \psi_x)(3s \psi_{xx})], \\
&= [(s^4 \psi_x^4 + 3s^3 \psi_x^2 + 4s^2 \psi_{xxx} \psi_x)(2s \psi_{xxx})], \\
&= [12s^2 \psi_x \psi_{xx} (6s^3 \psi_x^2 \psi_{xx} + s \psi_{xxxx})] - [3s^2 \psi_x^2 (6s^3 \psi_x^2 \psi_{xx} + s \psi_{xxxx})].
\end{align*}
\]
such that, for all $\psi$

The choice of the function $\psi$ given by (2.9) allows us to conclude that there exist $s_0 \geq 1$, $K > 0$ and $K_1 > 0$, such that, for all $s \geq s_0$,

$$2h_1(\psi) \geq Ks^7 \quad \text{for} \quad (x, t) \in \left(\frac{\eta}{2}, 2\pi - \frac{\eta}{2}\right) \times (0, T),$$

$$2h_2(\psi) \geq Ks^5 \quad \text{for} \quad (x, t) \in \left(\frac{\eta}{2}, 2\pi - \frac{\eta}{2}\right) \times (0, T),$$

$$2h_3(\psi) \geq Ks^3 \quad \text{for} \quad (x, t) \in \left(\frac{\eta}{2}, 2\pi - \frac{\eta}{2}\right) \times (0, T),$$

$$2h_4(\psi) \geq Ks \quad \text{for} \quad (x, t) \in \left(\frac{\eta}{2}, 2\pi - \frac{\eta}{2}\right) \times (0, T),$$

and, if $x \in \omega_0 = [0, \frac{\eta}{2}) \cup (2\pi - \frac{\eta}{2}, 2\pi)$,

$$|2h_1(\psi)| \leq K_1s^7 \quad \text{for} \quad (x, t) \in \omega_0 \times (0, T),$$

$$|2h_2(\psi)| \leq K_1s^5 \quad \text{for} \quad (x, t) \in \omega_0 \times (0, T),$$

$$|2h_3(\psi)| \leq K_1s^3 \quad \text{for} \quad (x, t) \in \omega_0 \times (0, T),$$

$$|2h_4(\psi)| \leq K_1s \quad \text{for} \quad (x, t) \in \omega_0 \times (0, T).$$

Consequently, for $s \geq s_0$, we obtain $C > 0$ satisfying

$$\|P_p v\|^2 + \int_T [s^7 |v|^2 + s^5 |v_x|^2 + s^3 |v_{xxx}|^2 + s|v_{xxxx}|^2] \, dx$$

$$= \|P_p v\|^2 + \int_{\omega_0} [s^7 |v_x|^2 + s^5 |v_x|^2 + s^3 |v_{xxx}|^2 + s|v_{xxxx}|^2] \, dx$$

$$+ \int_{T \setminus \omega_0} [s^7 |v_x|^2 + s^5 |v_x|^2 + s^3 |v_{xxx}|^2 + s|v_{xxxx}|^2] \, dx$$

$$\leq \|P_p v\|^2 + \int_{\omega_0} [2h_1(\psi)|v|^2 + 2h_2(\psi)|v_x|^2 + 2h_3(\psi)|v_{xxx}|^2 + 2h_4(\psi)|v_{xxxx}|^2] \, dx$$

$$+ C \int_{T \setminus \omega_0} [2h_1(\psi)|v|^2 + 2h_2(\psi)|v_x|^2 + 2h_3(\psi)|v_{xxx}|^2 + 2h_4(\psi)|v_{xxxx}|^2] \, dx$$

$$\leq \|P_p v\|^2 + \int_{\omega_0} [s^7 |v_x|^2 + s^5 |v_x|^2 + s^3 |v_{xxx}|^2 + s|v_{xxxx}|^2] \, dx$$

$$+ C \int_T [2h_1(\psi)|v|^2 + 2h_2(\psi)|v_x|^2 + 2h_3(\psi)|v_{xxx}|^2 + 2h_4(\psi)|v_{xxxx}|^2] \, dx$$
\[ \leq C \left( \| e^{s\psi} Pu \|^2 + \int_{\omega_0} [s^7 |v|^2 + s^5 |v_x|^2 + s^3 |v_{xxx}|^2 + s |v_{xxxx}|^2] dx \right), \]

that is,

\[ \| P_p v \|^2 + \int_T [s^7 |v|^2 + s^5 |v_x|^2 + s^3 |v_{xxx}|^2 + s |v_{xxxx}|^2] dx \leq C \left( \| e^{s\psi} Pu \|^2 + \int_{\omega_0} [s^7 |v|^2 + s^5 |v_x|^2 + s^3 |v_{xxx}|^2 + s |v_{xxxx}|^2] dx \right). \tag{2.18} \]

Observe that \( \int_T s^{-1} |v_{xxxx}|^2 dx \) is less than the right hand side of (2.18). Indeed,

\[
\int_T s^{-1} |v_{xxxx}|^2 dx = \int_T s^{-1} |P_p v|^2 + (s^4 \psi_x^2 + 3s^2 \psi_x^2 + 4s^2 \psi_{xxx} \psi_x) v - 12s^2 \psi_x \psi_{xxx} v_x - 6s^2 \psi_x^2 v_{xxx} |v|^2 dx \\
\leq C \int_T s^{-1} (|P_p v|^2 + |s^4 \psi_x^2 + 3s^2 \psi_x^2 + 4s^2 \psi_{xxx} \psi_x|^2 |v|^2 + 12s^2 \psi_x \psi_{xxx} |v_x|^2 + 6s^2 \psi_x^2 |v_{xxx}|^2) dx \\
\leq Cs^{-1} \left( \| P_p v \|^2 + \int_{\omega_0} (s^7 |v|^2 + s^5 |v_x|^2 + s^3 |v_{xxx}|^2) \right) \\
= C \left( s^{-1} \| P_p v \|^2 + \int_{\omega_0} (s^7 |v|^2 + s^5 |v_x|^2 + s^3 |v_{xxx}|^2) \right),
\]

for some \( C > 0 \). The above estimate and (2.18) leads to

\[
\int_T \left\{ s^{-1} |v_{xxxx}|^2 + s |v_{xxx}|^2 + s^3 |v_{xxx}|^2 + s^5 |v_x|^2 + s^7 |v|^2 \right\} dx \\
\leq C \left( s^{-1} \| P_p v \|^2 + \int_{\omega_0} (s^7 |v|^2 + s^5 |v_x|^2 + s^3 |v_{xxx}|^2) \right) \\
+ \int_{\omega_0} (s |v_{xxx}|^2 + s^3 |v_{xxx}|^2 + s^5 |v_x|^2 + s^7 |v|^2) \\
\leq C \left( s^{-1} \| P_p v \|^2 + \int_{\omega_0} (s |v_{xxx}|^2 + s^3 |v_{xxx}|^2 + s^5 |v_x|^2 + s^7 |v|^2) \right), \tag{2.19}
\]

where \( C \) does not depend on \( s \) and \( v \). In order to absorb the terms \( v_x \) and \( v_{xxx} \) above, let us consider \( \xi \in C_0^\infty (\omega) \) with \( 0 \leq \xi \leq 1 \) for \( x \in \omega_0 \). Then, observe that

\[
\int_{\omega_0} |v_x|^2 dx \leq \int_\omega \xi |v_x|^2 dx = \int_\omega \xi v_x v dx = - \int_\omega (\xi v_x + \xi v_{xx}) v dx \\
= \frac{1}{2} \int_\omega \xi v_{xx} v^2 dx - \int_\omega \xi v_{xxx} v dx,
\]

which allows us to deduce that

\[
2 \int_{\omega_0} s|v_x|^2 dx \leq \| \xi_{xx} \|_{L^\infty(T)} \int_\omega |v|^2 dx + \kappa \int_\omega s^{-1} |v_{xx}|^2 dx + \int_\omega s^3 |v|^2 dx \tag{2.20}
\]

and

\[
\int_{\omega_0} |v_{xxx}|^2 dx \leq \int_\omega \xi |v_{xxx}|^2 dx = \int_\omega \xi v_{xxx} v_{xxx} dx = - \int_\omega (\xi v_{xxx} + \xi v_{xxxx}) v_{xx} dx
\]
\[ \frac{1}{2} \int_\omega \xi_{xx} v_{xx}^2 dx - \int_\omega \xi v_{xxxx} v_{xx} dx. \]

Consequently,
\[ 2 \int_{\omega_0} s|v_{xxxx}|^2 dx \leq \|\xi_{xx}\|_{L^\infty(\Omega)} \int_\omega s|v_{xx}|^2 dx + \kappa \int_\omega s^{-1}|v_{xxxx}|^2 dx + \kappa^{-1} \int_\omega s^3|v_{xx}|^2 dx, \tag{2.21} \]

for any \( \kappa > 0 \). Combining (2.19), (2.20) and (2.21) with \( \kappa \) small enough and \( s \geq s_0 \) sufficiently large, for some constant \( C \) that does not depend on \( s \) and \( v \) we get
\[ \int_T \{s^{-1}|v_{xxxx}|^2 + s|v_{xxxx}|^2 + s^3|v_{xx}|^2 + s^5|v_x|^2 + s^7|v|^2 \} dx \leq C \left( \|e^{s\psi} Pu\|^2 + \int_\omega (s^7|v|^2 + s^3|v_{xx}|^2) dx \right). \tag{2.22} \]

Replacing \( v \) by \( e^{s\psi} u \) in (2.22) we obtain (2.15). The proof of Lemma 2.5 is complete.

We can now complete the proof of Proposition 2.3. Let \( u \in L^2(0,T;H^4(\Omega)) \) satisfying (2.2) and let \( w = u - b_1 u_{xx} + bu_{xxxx} \in L^2(0,T;L^2(\Omega)) \). Then,
\[ w_t + \frac{a}{b} w_x = \left( \frac{a}{b} - q \right) u_x - \left( \frac{ab_1}{b} + p \right) u_{xxx} - ru_{xx} \in L^2(0,T;L^2(\Omega)). \tag{2.23} \]

Combining (2.5), (2.6) (multiplied by \( e^{-2sp^c t^2} \) and next integrated over \( (0,T) \)) and (2.15), it follows that, for \( s \geq s_1 \), the following estimate holds
\[ \int_0^T \int_T \left[ \int_T |s|u_{xxx}|^2 + s^3|u_{xx}|^2 + s^5|u_x|^2 + s^7|u|^2 + s|u - b_1 u_{xx} + bu_{xxxx}|^2 \right] e^{2s\varphi} dx dt \]
\[ + \int_0^T \int_T \left[ |s|u - b_1 u_{xx} + bu_{xxxx} |^2 e^{2s\varphi} \right] \big|_{t=0} dx \]
\[ \leq C \int_0^T \int_T \left[ |u_{xxxx}|^2 + |(a/b - q) u_x - (ab_1/b + p) u_{xxx} - ru_{xx}|^2 \right] e^{2s\varphi} dx dt \]
\[ + C \int_0^T \int_\omega |s|u - b_1 u_{xx} + bu_{xxxx}|^2 + s^7|u|^2 + s^3|u_{xx}|^2 |e^{2s\varphi} dx dt. \]

Then, choosing \( s_2 \geq s_1 \) and \( C_2 > C \) large enough, we obtain (2.13) for any \( s \geq s_2 \) and any \( u \in L^2(0,T;H^4(\Omega)) \) satisfying (2.2).

Finally, we can prove Theorem 2.1.

- If \( u \in L^2(0,T;H^4(\Omega)) \) satisfies (2.2) and (2.3), it follows from the Carleman estimate (2.13) that \( u = 0 \) in \( T \times (0,T) \).
- If \( u \in L^\infty(0,T;H^3(\Omega)) \) we have to employ a slightly different approach, since Lemmas 2.5 and 2.4, employed to prove (2.13), cannot be applied directly. This is due to the lack of regularity of \( u \) and \( w = u - b_1 u_{xx} + bu_{xxxx} \), which solves (2.23). In order to overcome this difficulty, we first smooth them by making use of Proposition 2.6, stated below. More precisely, for any function \( g \) and any \( h > 0 \), we set
\[ g^{[h]}(x,t) = \frac{1}{h} \int_t^{t+h} g(x,s) ds. \]
Then, taking into account the regularity of the functions \( u^h \) and \( w^h \), as well as the equations of which they are solutions, we proceed as in the previous case and derive a Carleman estimate for the function \( u^h \). Finally, the unique continuation property is obtained by passing to the limit in this new estimate, as \( h \to 0 \). In order to do that, we employ Proposition 2.6 again.

We start the proof by stating Proposition 2.6 mention above (see, for instance, Prop. 1.4.29 in [6] and [11]):

**Proposition 2.6.** If \( X \) is a Banach space and \( g \in L^p(0, T, X) \), with \( 1 \leq p \leq \infty \), then for any \( h > 0 \) the function

\[
g^h(x, t) = \frac{1}{h} \int_t^{t+h} g(x, s) ds,
\]

satisfies

1. \( g^h \in W^{1,p}(0, T-h; X) \),
2. \( \|g^h\|_{L^p(0, T-h; X)} \leq \|g\|_{L^p(0, T; X)} \),
3. \( g^h \to g \) in \( L^p(0, T'; X) \), as \( h \to 0 \), for \( p < \infty \) and \( T' < T \).

Under the above conditions, pick any \( T' \in \left( \frac{2b_x}{a}, T \right) \). Then, for any positive number \( h < h_0 = T - T' \), the function \( u^h \in W^{1,\infty}(0, T'; H^3(\Omega)) \) and solves the equation

\[
u_t^h - b_1u_{xxxx} + bu_{xxxxx} + \left( (q(u)u_x)^h + (p(u)u_{xxx})^h + (r(u)u_{xx})^h \right) = 0 \quad \text{in} \quad L^\infty(0, T'; H^{-2}(\Omega)),
\]

where \( \nu_t^h \) denotes \( (v^h)_t \), \( \nu_x^h \) denotes \( (v^h)_x \), etc. Moreover,

\[
u^h(x, t) = 0 \quad \text{in} \quad (x, t) \in \omega \times (0, T').
\]

From (2.24), we infer that

\[
u_{xxxxx}^h = a^{-1}(-\nu_t^h + b_1u_{xxx}^h - bu_{xxxx}^h - (q(u)u_x)^h - (p(u)u_{xxx})^h - (r(u)u_{xx})^h).
\]

Hence, since the right hand side of the above identity belongs to \( L^\infty(0, T'; H^{-1}(\Omega)) \),

\[
u^h \in L^\infty(0, T'; H^1(\Omega)).
\]

This yields, with (2.5) and (2.6),

\[
u^h = \nu^h - b_1w_{xxx}^h + bw_{xxxx}^h \in L^\infty(0, T'; L^2(\Omega))
\]

and

\[
u_t^h + a\frac{q}{b}w_x^h = \left( \frac{ab_1}{b} - q \right)u_x^h - \left( \frac{ab_1}{b} + p \right)u_{xxx}^h - r_{xxx}^h \in L^\infty(0, T'; L^2(\Omega)).
\]
Thus, from (2.24)–(2.28), Lemma 2.5 and 2.4, we obtain constants \( s_1 > 0 \) and \( C_1 > 0 \), such that, for all \( s \geq s_1 \) and all \( h \in (0, h_0) \), we have

\[
\int_0^{T'} \int_T^t \left[ |u_{xxxx}^{[h]}|^2 + s^3 |u_x^{[h]}|^2 + s^5 |u_x^{[h]}|^2 + s^7 |u_x^{[h]}|^2 + s |u_{xxxx}^{[h]}|^2 \right] e^{2s\varphi} \, dx \, dt \\
\leq C \int_0^{T'} \int_T^t \left[ |(\frac{a}{b} - q) u_x^{[h]}| - \left(\frac{ab_1}{b} + p\right) u_{xxxx}^{[h]} - |ru_{xx}^{[h]}| \right]^2 e^{2s\varphi} \, dx \, dt \\
\leq C \int_0^{T'} \int_T^t \left[ |(\frac{a}{b} - q) u_x^{[h]}| - \left(\frac{ab_1}{b} + p\right) u_{xxxx}^{[h]} - |ru_{xx}^{[h]}| \right]^2 e^{2s\varphi} \, dx \, dt \\
\leq C \int_0^{T'} \int_T^t \left[ |(\frac{a}{b} - q) u_x^{[h]}| - \left(\frac{ab_1}{b} + p\right) u_{xxxx}^{[h]} - |ru_{xx}^{[h]}| \right]^2 e^{2s\varphi} \, dx \, dt \\
\leq C \int_0^{T'} \int_T^t \left[ |(\frac{a}{b} - q) u_x^{[h]}| - \left(\frac{ab_1}{b} + p\right) u_{xxxx}^{[h]} - |ru_{xx}^{[h]}| \right]^2 e^{2s\varphi} \, dx \, dt \\
+ C \int_0^{T'} \int_T^t \left[ |(\frac{a}{b} - q) u_x^{[h]}| - \left(\frac{ab_1}{b} + p\right) u_{xxxx}^{[h]} - |ru_{xx}^{[h]}| \right]^2 e^{2s\varphi} \, dx \, dt \\
+ C \int_0^{T'} \int_T^t \left[ |(\frac{a}{b} - q) u_x^{[h]}| - \left(\frac{ab_1}{b} + p\right) u_{xxxx}^{[h]} - |ru_{xx}^{[h]}| \right]^2 e^{2s\varphi} \, dx \, dt.
\]

Comparing the powers of \( s \) in (2.29), we obtain the following estimate for \( s \geq s_3 > s_1, h \in (0, h_0) \) and some constant \( C_3 > C_1 \) (that does not depend on \( s, h \)):

\[
\int_0^{T'} \int_T^t \left[ |u_{xxxx}^{[h]}|^2 + s^3 |u_x^{[h]}|^2 + s^5 |u_x^{[h]}|^2 + s^7 |u_x^{[h]}|^2 + s |u_{xxxx}^{[h]}|^2 \right] e^{2s\varphi} \, dx \, dt \\
\leq C \int_0^{T'} \int_T^t \left[ |(\frac{a}{b} - q) u_x^{[h]}| - \left(\frac{ab_1}{b} + p\right) u_{xxxx}^{[h]} - |ru_{xx}^{[h]}| \right]^2 e^{2s\varphi} \, dx \, dt \\
+ C \int_0^{T'} \int_T^t \left[ |(\frac{a}{b} - q) u_x^{[h]}| - \left(\frac{ab_1}{b} + p\right) u_{xxxx}^{[h]} - |ru_{xx}^{[h]}| \right]^2 e^{2s\varphi} \, dx \, dt \\
+ C \int_0^{T'} \int_T^t \left[ |(\frac{a}{b} - q) u_x^{[h]}| - \left(\frac{ab_1}{b} + p\right) u_{xxxx}^{[h]} - |ru_{xx}^{[h]}| \right]^2 e^{2s\varphi} \, dx \, dt.
\]

In order to pass to the limit in the right hand side of (2.30), we observe that, as \( h \to 0 \),

\[
\left(\frac{a}{b} - q\right) u_x^{[h]} \to \left(\frac{a}{b} - q\right) u_x \quad \text{in} \quad L^2(0, T'; L^2(\mathbb{T})), \\
\left(\frac{a}{b} - q\right) u_x^{[h]} \to \left(\frac{a}{b} - q\right) u_x \quad \text{in} \quad L^2(0, T'; L^2(\mathbb{T})), \\
\left(\frac{ab_1}{b} + p\right) u_{xxxx}^{[h]} \to \left(\frac{ab_1}{b} + p\right) u_{xxxx} \quad \text{in} \quad L^2(0, T'; L^2(\mathbb{T})), \\
\left(\frac{ab_1}{b} + p\right) u_{xxxx}^{[h]} \to \left(\frac{ab_1}{b} + p\right) u_{xxxx} \quad \text{in} \quad L^2(0, T'; L^2(\mathbb{T})), \\
|ru_{xx}^{[h]}| \to ru_{xx} \quad \text{in} \quad L^2(0, T'; L^2(\mathbb{T})), \\
ru_{x}^{[h]} \to ru_{x} \quad \text{in} \quad L^2(0, T'; L^2(\mathbb{T})),
\]

while \( e^{2s\varphi} \in L^\infty(\mathbb{T} \times (0, T')) \). Consequently, for fixed \( s \), we get

\[
\int_0^{T'} \int_T^t \left[ |(\frac{a}{b} - q) u_x^{[h]}| - \left(\frac{a}{b} - q\right) u_x^{[h]} |^2 e^{2s\varphi} \right] \, dx \, dt \to 0, \quad \text{as} \quad h \to 0,
\]
\[
\int_0^{T'} \int_T |(\frac{ab_1}{b} + p)u_{xxx}[h] - (\frac{ab_1}{b} + p)u_{xx}^{[h]}|2e^{2s3\varphi}dxdt \to 0, \text{ as } h \to 0,
\]
\[
\int_0^{T'} \int_T |ru_{xx}[h] - ru_{xx}^{[h]}|2e^{2s3\varphi}dxdt \to 0, \text{ as } h \to 0.
\]

The convergences above and (2.30) allow us to conclude that, as \(h \to 0\),
\[
\int_0^{T'} \int_T |u^{[h]}|2e^{2s3\varphi}dxdt \to 0.
\]

Since \(u^{[h]} \to u\) in \(L^2(0, T'; L^2(\mathbb{T}))\),
\[
\int_0^{T'} \int_T |u^{[h]}|^2e^{2s3\varphi}dxdt \to \int_0^{T'} \int_T |u|^2e^{2s3\varphi}dxdt,
\]
as \(h \to 0\). Therefore, we can conclude that \(u = 0\) in \(T \times (0, T')\). As \(T'\) may be taken arbitrarily close to \(T\), we infer that \(u = 0\) in \(T \times (0, T)\).

3. Exponential stabilization

Having the unique continuation result in hands, we derive the exponential decay of the solutions of (1.2) in the energy space \(H^2(\mathbb{T})\), as \(t \to \infty\). This is done under suitable assumptions on the initial data.

Before going into the stabilization problem, let us explain the expression of the damping \(\sigma\). We first write the linearized system of (1.2) as
\[
\begin{cases}
  u_t = Au + Bk, \\
  u(0) = u_0,
\end{cases}
\]
where \(A = -(I - b_1\partial_x^2 + b\partial_x^4)^{-1}(\partial_x + a_1\partial_x^3 + a_2\partial_x^5)\), \(k(t) = (I - b_1\partial_x^2 + b\partial_x^4)^{-1}h(t) \in L^2(0, T; H^s(\mathbb{T}))\) is a control input and
\[
B = (I - b_1\partial_x^2 + b\partial_x^4)^{-1}\sigma(I - b_1\partial_x^2 + b\partial_x^4).
\]

We know from [1] that \(A\) is skew-adjoint in \(H^s(\mathbb{T})\), and that (3.1) is exactly controllable in \(H^s(\mathbb{T})\). Moreover, if we choose the simple feedback law (see [8, 12])
\[
k = -B^{*,s}u
\]
the resulting closed-loop system
\[
\begin{cases}
  u_t = Au - BB^{*,s}u, \\
  u(0) = u_0
\end{cases}
\]
is exponentially stable in \(H^s(\mathbb{T})\), where \(B^{*,s}\) denotes the adjoint of \(B\) in \(\mathcal{L}(H^s(\mathbb{T}))\). It is shown in the Appendix that \(B^{*,s}\) is given by
\[
B^{*,s} = (1 - b\partial_x^2 + b_1\partial_x^4)^{-1}\sigma(1 - b\partial_x^2 + b_1\partial_x^4)^{-1}.
\]
We also deduce that
\[ B^{*,2}u = \sigma u. \]

In order to make the results stated above more precise, let \( \tilde{A} = A - BB^{*,2} \), where \((BB^{*,2})u = (I - b_1\partial^2_x + b\partial^4_x)[\sigma(I - b_1\partial^2_x + b\partial^4_x)(\sigma u)]\). Since \((BB^{*,2}) \in \mathcal{L}(H^4(\mathbb{T})) \) and \( A \) is skew adjoint in \( H^s(\mathbb{T}) \), \( \tilde{A} \) is the infinitesimal generator of a group \( \{W_a(t)\}_{t \in \mathbb{R}} \) on \( H^s(\mathbb{T}) \) (see [9], Thm. 3.4).

Then, we have the well-posedness and the following exponentially stabilization result for (3.1).

**Lemma 3.1.** Let \( \sigma \in C^\infty(\mathbb{T}) \) with \( \sigma \neq 0 \). Then, there exist a constant \( \beta > 0 \), such that, for \( s \geq 1 \), one can find a constant \( C_s > 0 \) for which the following holds for all \( u_0 \in H^s(\mathbb{T}) \):
\[
\|W_a(t)u_0\|_{H^s} \leq C_s e^{-\beta t}\|u_0\|_{H^s}, \quad \forall \ t \geq 0.
\] (3.5)

Adding the feedback law \( k = -B^{*,2}u = -\sigma u \) in the nonlinear equation (1.1) gives the closed-loop system (1.2). Then, Lemma 3.1 and the analysis developed in [5] give the following well-posedness result in the space \( H^s(\mathbb{T}) \) for \( s \geq 1 \):

**Theorem 3.2.** Let \( s \geq 1 \) and \( T > 0 \) be given. For any \( u_0 \in H^s(\mathbb{T}) \), the system (1.2) admits a unique solution \( u \in C([0,T]; H^s(\mathbb{T})) \).

The next steps are devoted to show that (1.2) is globally exponentially stable in the space \( H^2(\mathbb{T}) \). In order to do that, were start by proving the following observability inequality.

**Proposition 3.3.** Let \( R_0 > 0 \) and \( r > 0 \) be given. Then, there exist two positive number \( T \) and \( \theta \), such that, for any \( u_0 \in H^3(\mathbb{T}) \) satisfying
\[
0 < r \leq \|u_0\|_{H^2(\mathbb{T})} \quad \text{and} \quad \|u_0\|_{H^3(\mathbb{T})} \leq R_0,
\]
the corresponding solution \( u \) of (1.2) satisfies
\[
\|u_0\|_{H^2(\mathbb{T})}^2 \leq \theta \int_0^T \|\sigma u(t)\|^2_{H^2(\mathbb{T})}dt.
\] (3.6)

**Proof.** Let \( T > \frac{2\pi}{|\sigma|} \). We argue by contradiction and suppose that (3.6) is not true. In this case, for any \( n \geq 1 \), (1.2) admits a solution \( u_n \in C([0,T]; H^3(\mathbb{T})) \) satisfying
\[
0 < r \leq \|u_{0,n}\|_{H^2(\mathbb{T})} \quad \text{and} \quad \|u_{0,n}\|_{H^3(\mathbb{T})} \leq R_0
\] (3.7)
and
\[
\int_0^T \|\sigma u_n(t)\|^2_{H^2(\mathbb{T})}dt \leq \frac{1}{n} \|u_{0,n}\|^2_{H^2(\mathbb{T})},
\] (3.8)
where \( u_{0,n} = u_n(0) \). Since \( \alpha_n = \|u_{0,n}\|_{H^2(\mathbb{T})} \leq \|u_{0,n}\|_{H^3(\mathbb{T})} \leq R_0 \), we can choose a subsequence of \( (\alpha_n) \), still denoted by \( (\alpha_n)_{n \in \mathbb{N}} \), such that \( \lim_{n \to \infty} \alpha_n = \alpha \). Observe that, from (3.8), we obtain \( \alpha_n > 0 \).

Following the notation introduced above, we consider the function \( v_n = \frac{u_n}{\alpha_n} \), for all \( n \geq 1 \). Then, \( v_n \) satisfies
\[
v_{n,t} + v_{n,x} - b_1v_{n,txx} + a_1v_{n,xxx} + bv_{n,txxxx} + av_{n,xxxxx} + v_{n,xxxxx} = 0.
\]
\[
+ \frac{3}{2} \alpha_n v_{n,x} - \gamma \alpha_n (v^2_{n,x} - 7/48 \alpha_n (v^2_{n,x})_x - \frac{1}{8} \alpha_n^2 (v^3_{n,x})_x) - \sigma (I - b_1\partial^2_x + b\partial^4_x)\sigma v_n
\]
and
\[ \int_0^T \| \sigma v_n(t) \|^2_{H^2(T)} dt \leq \frac{1}{n}. \] (3.9)

Moreover,
\[ \| v_n(0) \|_{H^2(T)} = 1. \] (3.10)

Since
\[ \| v_n(0) \|_{H^3(T)} = \| u_n(0) \|_{H^3(T)} \leq R, \] for all \( n \in \mathbb{N} \), the sequence \((v_n)_{n \in \mathbb{N}} \) is bounded in \( L^\infty(0, T; H^3(T)) \) and \((v_n,t)_{n \in \mathbb{N}} \) is bounded in \( L^\infty(0, T; H^2(T)) \).

Then, from Aubin-Lions lemma, we deduce that \((v_n)_{n \in \mathbb{N}} \) is bounded in \( C(0, T; H^s(T)) \) for \( 2 < s < 3 \). Therefore, we can extract a subsequence of \((v_n)_{n \in \mathbb{N}} \), still denoted by \((v_n)_{n \in \mathbb{N}} \), such that
\[ v_n \to v \quad \text{in} \quad C(0, T; H^s(T)), \] (3.11)
\[ v_n \to v \quad \text{in} \quad L^\infty(0, T; H^3(T)) \quad \text{weak-*}, \] (3.12)

for some \( v \in L^\infty(0, T; H^3(T)) \cap C([0, T]; H^s(T)) \), for all \( 2 < s < 3 \). Consequently, from (3.11) and (3.12), we have that
\[ \alpha_n v_n v_{n,x} \to \alpha vv_x \quad \text{in} \quad L^\infty(0, T; L^2(T)) \quad \text{weak-*}, \]
\[ \alpha_n (v_n^2)_{xxx} \to (v^2)_{xxx} \quad \text{in} \quad L^\infty(0, T; L^2(T)) \quad \text{weak-*}, \]
\[ \alpha_n (v_n^3)_{x} \to (v^3)_{x} \quad \text{in} \quad L^\infty(0, T; L^2(T)) \quad \text{weak-*}. \]

Furthermore, by (3.9),
\[ \int_0^T \| \sigma v \|_{H^2(T)}^2 dt \leq \liminf_{n \to \infty} \int_0^T \| \sigma v_n \|_{H^2(T)}^2 dt = 0. \] (3.13)

Thus, \( v \) solves
\[
\begin{align*}
  & v_t + v_x - b_1 v_{1xx} + a_1 v_{xxx} + b v_{1xxxx} + \alpha v_{xxxxx} \\
  & + \frac{3}{2} \alpha vv_x - \gamma (v^2)_{xxx} - \frac{7}{48} (v^2)_x - \frac{1}{8} \alpha^2 (v^3)_x = -\sigma (I - b_1 \partial_x^2 + b \partial_x^4) \sigma v, \quad (x, t) \in T \times (0, T),
\end{align*}
\]
and, in addition,
\[ v = 0, \quad \text{in} \quad \omega \times (0, T). \]

From the UCP proved in Theorem 2.1 we conclude that \( v \equiv 0 \) in \( T \times (0, T) \).

In order to obtain a contradiction, we first claim that \((v_n)_{n \in \mathbb{N}} \) is linearizable in the sense of Proposition 9 in [7]. This is to say that, if \((w_n)_{n \in \mathbb{N}} \) denotes the sequence of solutions of the linear higher-order KdV–BBM
equation with the same initial data as follows

\[ w_{n,t} + w_{n,x} - b_1 w_{n,xx} + a_1 w_{xxxx} + bw_{xxxx} + aw_{xxxxx} = -\sigma(I - b_1 \partial_x^2 + b \partial_t^4)\sigma w_n, \]

\[ w_n(x,0) = v_n(x,0), \]

then

\[ \sup_{0 \leq t \leq T} \| v_n(t) - w_n(t) \|_{H^2(T)} \to 0, \quad \text{as} \quad n \to \infty. \]  

(3.15)

Indeed, if \( d_n = v_n - w_n \), then \( d_n \) solves

\[ d_{n,t} + d_{n,x} - b_1 d_{n,xx} + a_1 d_{n,xxxx} + bd_{n,xxxx} + ad_{n,xxxxx} = -\sigma(I - b_1 \partial_x^2 + b \partial_t^4)\sigma d_n - \frac{3}{2} \alpha_n v_n v_{n,x} - \gamma \alpha_n (v_n^2)_{xxx} + \frac{7}{48} \alpha_n (v_{n,x})^2 + \frac{1}{8} \alpha_n (v_n^3)_x \]

\[ d_n(0) = 0. \]

Since \( \| W_n(t) \|_{L^2(H^2(T))} \leq M e^{\omega t} \leq M e^\omega T \), with \( \omega, M > 0 \), from Duhamel formula we have that, for \( t \in [0, T] \),

\[ \| d_n(t) \|_{H^2(T)} \leq M e^{\omega T} \left( \int_0^T \| (I - b_1 \partial_x^2 + b \partial_t^4)^{-1} \frac{3}{2} \alpha_n v_n v_{n,x} \|_{H^2(T)} dt \\ + \int_0^T \| (I - b_1 \partial_x^2 + b \partial_t^4)^{-1} \gamma \alpha_n (v_n^2)_{xxx} \|_{H^2(T)} dt \\ + \int_0^T \| (I - b_1 \partial_x^2 + b \partial_t^4)^{-1} \frac{7}{48} \alpha_n (v_{n,x}^2) \|_{H^2(T)} dt \\ + \int_0^T \| (I - b_1 \partial_x^2 + b \partial_t^4)^{-1} \frac{1}{8} \alpha_n (v_n^3)_x \|_{H^2(T)} dt \right). \]

The above estimate combined with (3.11)–(3.12) and the fact that \( v \equiv 0 \) give us (3.15).

The next steps are devoted to prove that \( \| v_n(0) \|_{H^2(T)}^2 \to 0 \), as \( n \to \infty \). In fact, from Lemma 3.1 we have that

\[ \| w_n(t) \|_{H^2(T)} \leq c_1 e^{-\beta t} \| w_n(0) \|_{H^2(T)}, \quad \text{for all} \quad t \geq 0, \]  

(3.16)

and from the energy identity for (3.14), we get

\[ \| w_n(t) \|_{H^2(T)}^2 - \| w_n(0) \|_{H^2(T)}^2 = -2 \int_0^T \| \sigma w_n(t) \|_{H^2(T)}^2 dt \]

or

\[ \| w_n(0) \|_{H^2(T)}^2 = \| w_n(t) \|_{H^2(T)}^2 + 2 \int_0^T \| \sigma w_n(t) \|_{H^2(T)}^2 dt. \]
Therefore, from (3.16) it follows that
\[
\|w_n(0)\|^2_{H^2(T)} \leq 2(1 - c_1^2 e^{-2\beta T})^{-1} \left[ \int_0^T \|\sigma w_n(t) - \sigma v_n(t)\|^2_{H^2(T)} dt + \int_0^T \|\sigma v_n(t)\|^2_{H^2(T)} dt \right].
\] (3.17)

Estimate (3.17) combined with (3.9) and (3.15) yields \(\|v_n(0)\|^2_{H^2(T)} = \|w_n(0)\|^2_{H^2(T)} \to 0\), as \(n \to \infty\), which contradicts (3.10).

The main result of this section reads as follows:

**Theorem 3.4.** Let \(\sigma \in C^\infty(T)\) with \(\sigma \neq 0\), and \(\beta > 0\) be as given in Lemma 3.1. Then, for any \(R_0, r > 0\), there exists a constant \(C > 0\), such that, for any \(u_0 \in H^3(T)\) with \(0 < r \leq \|u_0\|_{H^2(T)}\) and \(\|u_0\|_{H^3(T)} \leq R_0\), the corresponding solution \(u\) of (1.2) satisfies
\[
\|u(\cdot, t)\|_{H^2(T)} \leq Ce^{-\beta t}\|u_0\|_{H^2(T)}.
\]

**Proof.** From Proposition 3.3 and the energy identity
\[
\|u(t)\|^2_{H^2(T)} = \|u(0)\|^2_{H^2(T)} - 2 \int_0^t \|\sigma u(\tau)\|^2_{H^2(T)} d\tau, \quad t \geq 0,
\]
we have
\[
\|u(T)\|^2_{H^2(T)} \leq (1 - 2\theta^{-1})\|u(0)\|^2_{H^2(T)}.
\]
Thus,
\[
\|u(kT)\|^2_{H^2(T)} \leq (1 - 2\theta^{-1})^k\|u(0)\|^2_{H^2(T)}, \quad k \in \mathbb{N},
\]
which, by the semigroup property, leads to
\[
\|u(t)\|^2_{H^2(T)} \leq Ce^{-\kappa t}\|u(0)\|^2_{H^2(T)}, \quad \text{for all} \quad t \geq 0.
\]

**APPENDIX A.**

Proof of Lemma 2.4: (see [11], Lem. 5.5):

We first assume that \(w \in H^1(T \times (0, T))\). Let \(v = e^{s\varphi}\) and \(P = \partial_t + \frac{a}{b}\partial_x\). Then
\[
e^{s\varphi}Pw = e^{s\varphi}P(e^{-s\varphi}v) \\
\quad = (-s\varphi_t v - \frac{a}{b}s\varphi_x v) + (v_t + \frac{a}{b}v_x) \\
\quad = P_n v + P_p v.
\]

It follows that
\[
\|e^{s\varphi}Pw\|^2_{L^2(T \times (0,T))} = \|P_n v\|^2_{L^2(T \times (0,T))} + \|P_p v\|^2_{L^2(T \times (0,T))} + 2\langle P_n v, P_p v \rangle_{L^2(T \times (0,T))}.
\] (A.1)
After some integrations by parts in $t$ and $x$ in the last term in (A.1), we obtain

$$2(P_v^0, P_v^0)_{L^2(\mathbb{T} \times (0,T))} = \int_0^T \int_{\mathbb{T}} s(\varphi_{tt} + \frac{2a}{b} \varphi_{xt} + \frac{a^2}{b^2} \varphi_{xx})v^2dxdt$$

$$- \int_0^T \int_{\mathbb{T}} s(\varphi_t + \frac{a}{b} \varphi_x)v^2(0,t)dx - \int_0^T \frac{a}{b}s(\varphi_t + \frac{a}{b} \varphi_x)v^2|_{0}^{T}dt. \quad (A.2)$$

Using (2.10)–(2.12) and the fact that $H_s$ for $n$ to the limit $w$ satisfies

We now claim that Lemma 2.4 is still true when $w$ which gives, at once, (2.14) by replacing $C$ and if ($w_0^n$) and $f_n$ are two sequences in $H^1(\mathbb{T})$ and $L^2(0,T; H^1(\mathbb{T}))$, respectively, such that

$$w_0^n \rightarrow w(0) \quad \text{in} \quad L^2(\mathbb{T})$$

$$f^n \rightarrow f \quad \text{in} \quad L^2(0,T; L^2(\mathbb{T})),$$

then the solution $w^n \in C([0,T]; H^1(\mathbb{T}))$ of

$$w_t^n + \frac{a}{b} w_x^n + f^n,$$

$$w^n(0) = w_0^n$$

satisfies $w^n \in H^1(\mathbb{T} \times (0,T))$ and $w^n \rightarrow w$ in $C([0,T]; L^2(\mathbb{T}))$, so that we can apply (2.14) to $w^n$ and then pass to the limit $n \rightarrow \infty$. The proof of Lemma 2.4 is complete.

**Proof of (3.4):**

Observe that

$$c_{b,b_1}(1 + bx^2 + b_1 x^4)^\frac{s}{2} \leq [(1 + x^2)^2]^\frac{s}{2} \leq C_{b,b_1}(1 + bx^2 + b_1 x^4)^\frac{s}{2},$$

for $s \geq 2$ and some positive constants $c_{b,b_1}, C_{b,b_1}$. Then, we can define the following equivalent inner product in $H^s(\mathbb{T})$ as

$$(u, v)_s = \int_{\mathbb{T}} (1 + bx^2 + b_1 x^4)^\frac{s}{2} F_u(x) \overline{F_v(x)} dx,$$
where $\mathcal{F} \varphi$ denote the Fourier transform of $\varphi$. Hence, employing Plancherel Theorem, we get

\[
(B\varphi, \psi)_s = \int_{\mathbb{T}} \left(1 + bx^2 + b_1 x^4\right)^{\frac{s}{2}} \mathcal{F}[(1 - b\partial_x^2 + b_1 \partial_x^4)^{-1} \sigma(x)(1 - b\partial_x^2 + b_1 \partial_x^4)\varphi(x)] \mathcal{F} \psi(x) dx
\]

\[
= \int_{\mathbb{T}} \left(1 + bx^2 + b_1 x^4\right)^{\frac{s}{2}} \mathcal{F}[\sigma(x)(1 - b\partial_x^2 + b_1 \partial_x^4)\varphi(x)] \mathcal{F} \psi(x) dx
\]

\[
= \int_{\mathbb{T}} \mathcal{F}[\sigma(x)(1 - b\partial_x^2 + b_1 \partial_x^4)\varphi(x)] \mathcal{F}[(1 - b\partial_x^2 + b_1 \partial_x^4)^{\frac{s}{2}} \sigma(x)] \mathcal{F} \psi(x) dx
\]

\[
= (\sigma(x)(1 - b\partial_x^2 + b_1 \partial_x^4)\varphi, (1 - b\partial_x^2 + b_1 \partial_x^4)^{\frac{s}{2}} \sigma(x))_{L^2(\mathbb{T})}
\]

\[
= (1 - b\partial_x^2 + b_1 \partial_x^4)\varphi, \sigma(x)(1 - b\partial_x^2 + b_1 \partial_x^4)^{\frac{s}{2}} \sigma(x))_{L^2(\mathbb{T})}
\]

\[
= \int_{\mathbb{T}} \mathcal{F}[(1 - b\partial_x^2 + b_1 \partial_x^4)\varphi(x)] \mathcal{F}[(1 - b\partial_x^2 + b_1 \partial_x^4)^{\frac{s}{2}} \sigma(x)] \mathcal{F} \psi(x) dx
\]

\[
= \int_{\mathbb{T}} \left(1 + bx^2 + b_1 x^4\right)^{\frac{s}{2}} \mathcal{F} \varphi(x)(1 + bx^2 + b_1 x^4)^{1 - \frac{s}{2}} \mathcal{F}[(1 - b\partial_x^2 + b_1 \partial_x^4)^{\frac{s}{2}} \sigma(x)] \mathcal{F} \psi(x) dx
\]

\[
= (\varphi, (1 - b\partial_x^2 + b_1 \partial_x^4)^{1-\frac{s}{2}} \sigma(x)(1 - b\partial_x^2 + b_1 \partial_x^4)^{\frac{s}{2}} \psi)_s
\]

for all $\varphi, \psi \in H^s(\mathbb{T})$. From the computation above we deduce (3.4).

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References


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