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A note on Carleman estimates and Unique continuation property for the Boussinesq system

Youcef Mammeri

Laboratoire Amiénois de Mathématique Fondamentale et Appliquée,
CNRS UMR 7352, Université de Picardie Jules Verne,
80069 Amiens, France.

Email: youcef.mammeri@u-picardie.fr

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Abstract. A Carleman estimates is established to prove a unique continuation property of the solution of the Boussinesq system. We can prove that if the solution of the Boussinesq systems vanishes in an open subset, then this solution is identically equal to zero in the horizontal component of the open subset.

Keywords. Boussinesq system, Carleman estimates, UCP, Treves' inequality.

MS Codes. 35B60, 35Q53.

1 Introduction

The two-way propagation of small amplitude, long wavelength, gravity waves in shallow water, described by its surface η and its velocity u , was first derived by Boussinesq [5] as a system of the form

$$\begin{aligned}\eta_t + u_x + (\eta u)_x &= 0 \\ u_t + \eta_x + uu_x - u_{xxt} &= 0.\end{aligned}$$

In this paper, we consider the following generalized regularized Boussinesq system, proposed in [2, 3], for $\rho \geq 1$ an integer,

$$\begin{aligned}\eta_t + u_x + (\eta^\rho u)_x + au_{xxx} - b\eta_{xxt} &= 0 \\ u_t + \eta_x + u^\rho u_x + c\eta_{xxx} - du_{xxt} &= 0.\end{aligned}$$

The purpose of this work is to prove a unique continuation property. More precisely, we show that if $(\eta, u) = (\eta(x, t), u(x, t))$ is solution of the system and (η, u) vanishes on an open subset Ω of $\mathbb{R} \times \mathbb{R}$, then u vanishes identically on the horizontal component $\Omega_h := \{(x, t) \in \mathbb{R} \times \mathbb{R}; \exists x_1 \text{ with } (x_1, t) \in \Omega\}$ of Ω .

Carleman estimates can be used. These estimates are based on exponential weight for the solution of the equation. More precisely, if v is solution of $\mathcal{L}v = Vv$, with \mathcal{L} a linear operator, V a well-defined potential, the Carleman estimates is written for Ψ a convex function and $\tau > 0$ to choose

$$\|e^{\tau\Psi(x)}v\| \leq C\|e^{\tau\Psi(x)}\mathcal{L}v\|.$$

Saut and Scheurer [12] proved such a result for a general class of dispersive equations, including the Korteweg-de Vries one. An alternative approach was suggested by Bourgain [4]. The method here is

based on an analytic continuation of the Fourier transform using the theorem of Paley-Wiener. We proved therefore a unique continuation property of the solution of the Boussinesq systems with $b = d = 0$ [10]. The method of Bourgain depends on the dispersion relation σ which has to satisfy the following growth property: $\forall R > 0, \exists |k| > R$ such that

$$\sigma'(k) \geq f(k) \text{ with } \lim_{|k| \rightarrow \infty} f(k) = +\infty.$$

In the case of the Boussinesq systems, we obtain

$$\sigma(k) = k \sqrt{\frac{(1 - ak^2)(1 - ck^2)}{(1 + bk^2)(1 + dk^2)}},$$

and the property holds if $b = d = 0$.

We propose here to prove a unique continuation property using a Carleman estimate. We are inspired by a work of Davila and Menzala [7] who proved a unique continuation property of the scalar one-dimensional Benjamin-Bona-Mahony equation. The first section is devoted to the local well-posedness of solution of the generalized Boussinesq system. We establish a Carleman estimates in the second section. The third section deals with the unique continuation property.

2 Initial value problem

We consider the initial value problem, for $x \in \mathbb{R}, t \in \mathbb{R}, \rho \geq 1$ an integer,

$$\begin{aligned} \eta_t + u_x + (\eta^\rho u)_x + au_{xxx} - b\eta_{xxt} &= 0 \\ u_t + \eta_x + u^\rho u_x + c\eta_{xxx} - d\eta_{xxt} &= 0 \\ \eta(x, 0) = \eta_0(x), u(x, 0) = u_0(x). \end{aligned}$$

If $\rho = 1$, it has been proved the existence and uniqueness of local in time solution [2, 3]. We denote $H^s(\mathbb{R})$ the Sobolev space of order s equipped with the norm $\|u\|_s$.

Theorem 2.1

Let $a, b, c, d > 0, s > 1/2$ and $(\eta_0, u_0) \in H^s(\mathbb{R}) \times H^s(\mathbb{R})$. There exists a constant $C_0 > 0$, depending only on s , such that for

$$T = \frac{C_0}{(\|\eta_0\|_s + \|u_0\|_s)^\rho},$$

there exists a unique solution $(\eta, u) \in \mathcal{C}([-T, T]; H^s(\mathbb{R})) \times \mathcal{C}([-T, T]; H^s(\mathbb{R}))$ of the Boussinesq system with (η_0, u_0) as initial datum.

Moreover, for all $M > 0$ with $\|\eta_0\|_s + \|u_0\|_s \leq M$ and $\|\mu_0\|_s + \|v_0\|_s \leq M$, there exists $C_1 > 0$ such that solutions (η, u) and (μ, v) , of initial data (η_0, u_0) and (μ_0, v_0) respectively, satisfy for $t \in [-T, T]$, with $T = C_0/M^\rho$,

$$\|\eta(t) - \mu(t)\|_s + \|u(t) - v(t)\|_s \leq C_1(\|\eta_0 - \mu_0\|_s + \|u_0 - v_0\|_s).$$

Proof. Let $T > 0$. The Duhamel's formula implies that (η, u) is the solution of the initial value problem if and only if (η, u) is the solution of the following equation, for $t \in [0, T]$,

$$(\eta, u)(t) = \Phi(\eta, u)(t) := S_t(\eta_0, u_0) - \int_0^t S_{t-\tau} \left(\frac{\partial_x(\eta^\rho u)}{1 - b\partial_x^2}, \frac{\partial_x(u^{\rho+1})/(\rho+1)}{1 - d\partial_x^2} \right) (\tau) d\tau, \quad (2.1)$$

with

$$S_t(\eta, u) := \int_{-\infty}^{+\infty} e^{-ikA(k)t}(\eta, u)dk \text{ and } A(k) = \begin{pmatrix} 0 & \frac{1-ak^2}{1+bk^2} \\ \frac{1-ck^2}{1+dk^2} & 0 \end{pmatrix}. \quad (2.2)$$

The eigenvalues of $A(k)$ are

$$\sigma(k) = \pm \sqrt{\frac{(1 - ak^2)(1 - ck^2)}{(1 + bk^2)(1 + dk^2)}},$$

and the matrix $e^{-ikA(k)t}$ is uniformly bounded.

We aim at applying the fixed point theorem. We deduce, for $t \in [0, T]$,

$$\|\Phi(\eta, u)(t)\|_s \leq C(\|\eta_0\|_s + \|u_0\|_s) + C \int_0^t \left\| \frac{\partial_x(\eta^\rho u)}{1 - b\partial_x^2} \right\|_s + \left\| \frac{\partial_x(u^{\rho+1})}{1 - d\partial_x^2} \right\|_s(\tau) d\tau.$$

For $b > 0$, the definition of the Sobolev norm provides

$$\left\| \frac{\partial_x f}{1 - b\partial_x^2} \right\|_s = \left(\int_{-\infty}^{+\infty} (1 + k^2)^s \left| \frac{ik}{1 + bk^2} \widehat{f}(k) \right|^2 \right)^{1/2} \leq C \|f\|_s.$$

Since $s > 1/2$, the Sobolev space being an algebra, the Sobolev embedding implies that there exists a constant $C_s > 0$, depending only on s , such that

$$\|\Phi(\eta, u)(t)\|_s \leq C(\|\eta_0\|_s + \|u_0\|_s) + C_s T \left(\sup_{t \in [0, T]} (\|u\|_s \|\eta\|_s^\rho + \|u(t)\|_s^{\rho+1}) \right). \quad (2.3)$$

Then there exists $C_0 > 0$ such that for $T = C_0 / (\|\eta_0\|_s + \|u_0\|_s)^\rho$, the closed ball \overline{B}_T defined by

$$\begin{aligned} \sup_{t \in [0, T]} \|\eta(t)\|_s &\leq 2C(\|\eta_0\|_s + \|u_0\|_s) \\ \sup_{t \in [0, T]} \|u(t)\|_s &\leq 2C(\|\eta_0\|_s + \|u_0\|_s) \end{aligned}$$

satisfies $\Phi(\overline{B}_T) \subseteq \overline{B}_T$. Indeed, let $(\eta, u) \in \overline{B}_T$, the inequality (2.3) becomes

$$\|\Phi(\eta, u)(t)\|_s \leq (\|\eta_0\|_s + \|u_0\|_s) C(1 + 2^{\rho+2} C^\rho C_s C_0),$$

and $C(\|\eta_0\|_s + \|u_0\|_s) C(1 + 2^{\rho+2} C^\rho C_s C_0) \leq 2C(\|\eta_0\|_s + \|u_0\|_s)$ if $C_0 \leq 1 / (2^{\rho+2} C^\rho C_s)$.

Let (η, u) and (μ, v) be in \overline{B}_T . The Duhamel's formula (2.1) provides, for $t \in [0, T]$,

$$\|\Phi(\eta, u)(t) - \Phi(\mu, v)(t)\|_s \leq C \int_0^t \left\| \frac{\partial_x}{1 - b\partial_x^2} (\eta^\rho u - \mu^\rho v) \right\|_s + \left\| \frac{\partial_x}{1 - d\partial_x^2} (u^{\rho+1} - v^{\rho+1}) \right\|_s(\tau) d\tau.$$

We can note that

$$\eta^\rho u - \mu^\rho v = \eta^\rho(u - v) + v(\eta - \mu) \sum_{i=0}^{\rho-1} \eta^{\rho-1-i} \mu^i, \text{ and } u^{\rho+1} - v^{\rho+1} = (u - v) \sum_{i=0}^{\rho} u^{\rho-i} v^i.$$

This provides, thanks to the Sobolev embedding,

$$\begin{aligned} \|\Phi(\eta, u)(t) - \Phi(\mu, v)(t)\|_s &\leq 2^\rho C^\rho C_s T (\|\eta_0\|_s + \|u_0\|_s)^\rho \left(\sup_{t \in [-T, T]} (\|\eta - \mu\|_s(t) + \|u - v\|_s(t)) \right) \\ &= 2^\rho C^\rho C_s C_0 \left(\sup_{t \in [-T, T]} (\|\eta - \mu\|_s(t) + \|u - v\|_s(t)) \right). \end{aligned}$$

For $C_0 < 1/(2^\rho C^\rho C_s)$, the map Φ is a contraction on \overline{B}_T . Finally, according to the fixed point theorem, there exists a unique solution (η, u) of $\Phi(\eta, u)(t) = (\eta, u)(t)$ in \overline{B}_T .

It remains to prove the continuity with the initial datum. Let (η, u) and (μ, v) be solutions of the initial value problem with initial datum (η_0, u_0) and (μ_0, v_0) respectively, such that $\|\eta_0\|_s + \|u_0\|_s \leq M$ and $\|\mu_0\|_s + \|v_0\|_s \leq M$. The Duhamel's formula (2.1) gives for $t \in [0, T]$, with $T = C_0/M^\rho$, with $C_0 \ll 1$,

$$\begin{aligned} \|(\eta, u)(t) - (\mu, v)(t)\|_s &\leq C(\|\eta_0 - \mu_0\|_s + \|u_0 - v_0\|_s) \\ &\quad + C \int_0^t \left\| \frac{\partial_x}{1 - b\partial_x^2}(\eta^\rho u - \mu^\rho v) \right\|_s + \left\| \frac{\partial_x}{1 - d\partial_x^2}(u^{\rho+1} - v^{\rho+1}) \right\|_s (\tau) d\tau \\ &\leq C(\|\eta_0 - \mu_0\|_s + \|u_0 - v_0\|_s) + \frac{1}{2} \left(\sup_{t \in [0, T]} \|\eta - \mu\|_s(t) + \sup_{t \in [0, T]} \|u - v\|_s(t) \right), \end{aligned}$$

thus

$$\sup_{t \in [0, T]} (\|\eta - \mu\|_s + \|u - v\|_s) \leq 2C(\|\eta_0 - \mu_0\|_s + \|u_0 - v_0\|_s).$$

□

3 Carleman estimates

The aim of this section is to find a Carleman estimates for the Boussinesq system. First we recall the Treves' inequality [13].

Theorem 3.1

Let $P = P(\partial_x, \partial_t)$ be a differential operator of order m with constant coefficients. Then for all $\alpha = (\alpha_1, \alpha_2) \in \mathbb{N}^2, \delta > 0, \tau > 0, \Phi \in \mathcal{C}_0^\infty(\mathbb{R}^2)$ and $\Psi(x, t) = (x - \delta)^2 + \delta^2 t^2$,

$$\frac{2^{2|\alpha|} \tau^{|\alpha|} \delta^{2\alpha_2}}{\alpha!} \int_{\mathbb{R}^2} |P^{(\alpha)}(D)\Phi|^2 e^{2\tau\Psi} dx dt \leq C(m, \alpha) \int_{\mathbb{R}^2} |P(D)\Phi|^2 e^{2\tau\Psi} dx dt.$$

with

$$|\alpha| = \sum_{j=1}^n \alpha_j, \alpha! = \alpha_1! \dots \alpha_n! \text{ and } C(m, \alpha) = \begin{cases} \sup_{|r+\alpha| \leq m} \binom{r+\alpha}{\alpha} & \text{if } |\alpha| \leq m \\ 0 & \text{if } |\alpha| > m \end{cases}$$

This inequality is used to prove Carleman estimates of the Boussinesq system.

Theorem 3.2

We define

$$\mathcal{L} := \begin{pmatrix} \partial_t - c_1 \partial_{xxt} + c_2 \partial_{xxx} + f_{1,1}(x, t) \partial_x & a \partial_{xxx} + f_{1,2}(x, t) \partial_x \\ c \partial_{xxx} + f_{2,1}(x, t) \partial_x & \partial_t - c_3 \partial_{xxt} + c_4 \partial_{xxx} + f_{2,2}(x, t) \partial_x \end{pmatrix},$$

where c_1, c_2, c_3, c_4 are constant in \mathbb{R} , $f_{i,j} \in L^\infty(\mathbb{R}^2), 1 \leq i, j \leq 2$. Let $\delta > 0$ and $B_\delta := \{(x, t) \in \mathbb{R}^2; x^2 + t^2 < \delta^2\}$. Then, there exists $C > 0$ such that for all $\Phi = (\Phi_1, \Phi_2) \in \mathcal{C}_0^\infty(B_\delta) \times \mathcal{C}_0^\infty(B_\delta)$, $\Psi(x, t) = (x - \delta)^2 + \delta^2 t^2$ and $\tau > 0$ with

$$\frac{\|f_{1,1}\|_\infty^2}{c_1 \tau^2 \delta^2} \leq \frac{1}{4}, \frac{\|f_{2,2}\|_\infty^2}{c_3 \tau^2 \delta^2} \leq \frac{1}{4}, \frac{\|f_{2,1}\|_\infty^2}{c^2 \tau^2} \leq \frac{1}{4}, \frac{\|f_{1,2}\|_\infty^2}{a^2 \tau^2} \leq \frac{1}{4},$$

we have

$$\tau^3 \int_{B_\delta} (|\Phi_1|^2 + |\Phi_2|^2) e^{2\tau\Psi} dx dt + \tau^2 \delta^2 \int_{B_\delta} (|\Phi_{1,x}|^2 + |\Phi_{2,x}|^2) e^{2\tau\Psi} dx dt \leq C \int_{B_\delta} |\mathcal{L}\Phi|^2 e^{2\tau\Psi} dx dt. \quad (3.1)$$

Proof. We define the differential operator

$$P := \begin{pmatrix} \partial_t - c_1 \partial_{xxt} + c_2 \partial_{xxx} & a \partial_{xxx} \\ c \partial_{xxx} & \partial_t - c_3 \partial_{xxt} + c_4 \partial_{xxx} \end{pmatrix}.$$

The Fourier transform gives for $(\xi_1, \xi_2, \tau) \in \mathbb{R}^3$

$$\widehat{P}(\xi, \tau) = i \begin{pmatrix} \tau + c_1 \xi^2 \tau - c_2 \xi^3 & -a \xi^3 \\ -c \xi^3 & \tau + c_3 \xi^2 \tau - c_4 \xi^3 \end{pmatrix}.$$

Lemma 3.3

For all $\Phi = (\Phi_1, \Phi_2) \in \mathcal{C}_0^\infty(B_\delta) \times \mathcal{C}_0^\infty(B_\delta)$, $\Psi(x, t) = (x - \delta)^2 + \delta^2 t^2$ and $\tau > 0$, we have

$$\begin{aligned} & \tau^3 (c_2^2 + c^2) \int_{B_\delta} |\Phi_1|^2 e^{2\tau\Psi} dxdt + \tau^2 (c_1^2 \delta^2 + c^2) \int_{B_\delta} |\Phi_{1,x}|^2 e^{2\tau\Psi} dxdt \\ & + \tau^3 (c_4^2 + a^2) \int_{B_\delta} |\Phi_2|^2 e^{2\tau\Psi} dxdt + \tau^2 (c_3^2 \delta^2 + a^2) \int_{B_\delta} |\Phi_{2,x}|^2 e^{2\tau\Psi} dxdt \leq \int_{B_\delta} |P\Phi|^2 e^{2\tau\Psi} dxdt. \end{aligned}$$

Proof. With the same notations of Treves' inequality, we have for $\alpha = (3, 0)$

$$\frac{\widehat{P_{1,1}}^{|\alpha|}(\xi, \tau)}{\partial \xi^3} = -i6c_2, P^{|\alpha|}\Phi_1 = -i6c_2\Phi_1, C(3, (3, 0)) = \sup_{|r+\alpha| \leq 3} \binom{r+\alpha}{\alpha} = 1.$$

Applying the preceding corollary with $P_{1,1}$ and α gives

$$\frac{2^6 \tau^3}{6} \int_{\mathbb{R}^2} |-i6c_2\Phi_1|^2 e^{2\tau\Psi} dxdt \leq \int_{\mathbb{R}^2} |P_{1,1}\Phi_1|^2 e^{2\tau\Psi} dxdt,$$

what implies

$$\tau^3 c_2^2 \int_{\mathbb{R}^2} |\Phi_1|^2 e^{2\tau\Psi} dxdt \leq \int_{\mathbb{R}^2} |P_{1,1}\Phi_1|^2 e^{2\tau\Psi} dxdt.$$

In the same way, we obtain for $\alpha = (1, 1)$

$$\frac{\widehat{P_{1,1}}^{|\alpha|}(\xi, \tau)}{\partial \xi^2 \partial \tau} = i2c_1\xi, P^{|\alpha|}\Phi_1 = 2c_1\Phi_{1,x}, C(3, (1, 1)) = 2,$$

and the Treves' inequality provides

$$\frac{2^4 \tau^2 \delta^2}{1} \int_{\mathbb{R}^3} |2c_1\Phi_{1,x}|^2 e^{2\tau\Psi} dxdt \leq 2 \int_{\mathbb{R}^3} |P_{1,1}\Phi_1|^2 e^{2\tau\Psi} dxdt,$$

thus

$$\tau^2 c_1^2 \int_{\mathbb{R}^2} |\Phi_{1,x}|^2 e^{2\tau\Psi} dxdt \leq \int_{\mathbb{R}^2} |P_{1,1}\Phi_1|^2 e^{2\tau\Psi} dxdt.$$

On the other hand, we have for $\alpha = (3, 0)$, respectively $\alpha = (2, 0)$,

$$\begin{aligned} \frac{\widehat{P_{2,1}}^{|\alpha|}(\xi, \tau)}{\partial \xi^3} &= -i6c, P_{2,1}^{|\alpha|}\Phi_1 = -i6c\Phi_1, C(3, (3, 0)) = 1 \\ \frac{\widehat{P_{2,1}}^{|\alpha|}(\xi, \tau)}{\partial \xi^2} &= -i6c\xi, P_{2,1}^{|\alpha|}\Phi_1 = 6c\Phi_{1,x}, C(3, (2, 0)) = 1. \end{aligned}$$

The Treves'inequality given by the preceding corollary with $P_{2,1}$ and α gives

$$\begin{aligned}\tau^3 c^2 \int_{\mathbb{R}^2} |\Phi_1|^2 e^{2\tau\Psi} dxdt &\leq \int_{\mathbb{R}^2} |P_{2,1}\Phi_1|^2 e^{2\tau\Psi} dxdt \\ \tau^2 c_1^2 \int_{\mathbb{R}^2} |\Phi_{1,x}|^2 e^{2\tau\Psi} dxdt &\leq \int_{\mathbb{R}^2} |P_{2,1}\Phi_1|^2 e^{2\tau\Psi} dxdt.\end{aligned}$$

We obtain similar inequalities for $P_{1,2}$ and $P_{2,2}$ in the same way. \square

Lemma 3.4

We have

$$\begin{aligned}\int_{B_\delta} |f_{1,1}(x,t)\Phi_{1,x}|^2 e^{2\tau\Psi} dxdt &\leq \frac{2\|f_{1,1}\|_\infty^2}{c_1^2 \tau^2 \delta^2} \left(\int_{B_\delta} |\mathcal{L}_{1,1}\Phi_1|^2 e^{2\tau\Psi} dxdt + \int_{B_\delta} |f_{1,1}(x,t)\Phi_{1,x}|^2 e^{2\tau\Psi} dxdt \right) \\ \int_{B_\delta} |f_{2,2}(x,t)\Phi_{2,x}|^2 e^{2\tau\Psi} dxdt &\leq \frac{2\|f_{2,2}\|_\infty^2}{c_3^2 \tau^2 \delta^2} \left(\int_{B_\delta} |\mathcal{L}_{2,2}\Phi_2|^2 e^{2\tau\Psi} dxdt + \int_{B_\delta} |f_{2,2}(x,t)\Phi_{2,x}|^2 e^{2\tau\Psi} dxdt \right) \\ \int_{B_\delta} |f_{2,1}(x,t)\Phi_{1,x}|^2 e^{2\tau\Psi} dxdt &\leq \frac{2\|f_{2,1}\|_\infty^2}{c^2 \tau^2} \left(\int_{B_\delta} |\mathcal{L}_{2,1}\Phi_1|^2 e^{2\tau\Psi} dxdt + \int_{B_\delta} |f_{2,1}(x,t)\Phi_{1,x}|^2 e^{2\tau\Psi} dxdt \right) \\ \int_{B_\delta} |f_{1,2}(x,t)\Phi_{2,x}|^2 e^{2\tau\Psi} dxdt &\leq \frac{2\|f_{1,2}\|_\infty^2}{a^2 \tau^2} \left(\int_{B_\delta} |\mathcal{L}_{1,2}\Phi_1|^2 e^{2\tau\Psi} dxdt + \int_{B_\delta} |f_{1,2}(x,t)\Phi_{2,x}|^2 e^{2\tau\Psi} dxdt \right).\end{aligned}$$

Proof. We have thanks to the above lemma

$$\begin{aligned}\int_{B_\delta} |f_{1,1}(x,t)\Phi_{1,x}|^2 e^{2\tau\Psi} dxdt &\leq \|f_{1,1}\|_\infty^2 \int_{B_\delta} |\Phi_{1,x}|^2 e^{2\tau\Psi} dxdt \\ &\leq \frac{\|f_{1,1}\|_\infty^2}{c_1^2 \tau^2 \delta^2} \int_{B_\delta} |P_{1,1}\Phi_1|^2 e^{2\tau\Psi} dxdt \\ &\leq \frac{2\|f_{1,1}\|_\infty^2}{c_1^2 \tau^2 \delta^2} \int_{B_\delta} (|\mathcal{L}_{1,1}\Phi_1|^2 + |f_{1,1}(x,t)\Phi_{1,x}|^2) e^{2\tau\Psi} dxdt.\end{aligned}$$

In the same manner, it gets

$$\begin{aligned}\int_{B_\delta} |f_{2,1}(x,t)\Phi_{1,x}|^2 e^{2\tau\Psi} dxdt &\leq \|f_{2,1}\|_\infty^2 \int_{B_\delta} |\Phi_{1,x}|^2 e^{2\tau\Psi} dxdt \\ &\leq \frac{\|f_{2,1}\|_\infty^2}{c^2 \tau^2} \int_{B_\delta} |P_{2,1}\Phi_1|^2 e^{2\tau\Psi} dxdt \\ &\leq \frac{2\|f_{2,1}\|_\infty^2}{c^2 \tau^2} \int_{B_\delta} (|\mathcal{L}_{2,1}\Phi_1|^2 + |f_{2,1}(x,t)\Phi_{1,x}|^2) e^{2\tau\Psi} dxdt.\end{aligned}$$

We obtain similar inequalities for $f_{1,2}$ and $f_{2,2}$ in the same way. \square

To conclude, it is enough to choose $\tau > 0$ large enough with

$$\frac{2\|f_{1,1}\|_\infty^2}{c_1 \tau^2 \delta^2} \leq \frac{1}{2}, \quad \frac{2\|f_{2,2}\|_\infty^2}{c_3 \tau^2 \delta^2} \leq \frac{1}{2}, \quad \frac{2\|f_{2,1}\|_\infty^2}{c^2 \tau^2} \leq \frac{1}{2}, \quad \frac{2\|f_{1,2}\|_\infty^2}{a^2 \tau^2} \leq \frac{1}{2}.$$

\square

Corollary 3.5

Let $T > 0$. If $\Phi \in (\mathcal{C}^1([-T, T]; H^3(\mathbb{R})))^2$, $\Phi_t \in (\mathcal{C}^1([-T, T]; H^2(\mathbb{R})))^2$ and $\text{supp } \Phi \subseteq B_\delta \times B_\delta$, the inequality (3.1) remains true.

Proof. The proof is done by regularization. □

4 Unique continuation property

The unique continuation property is now proven. The proof is similar to the scalar case of the paper of Davila and Menzala [7]. Therefore we only write sketch of the proof for easy to read.

Lemma 4.1

Let $s \geq 5, T > 0, f_{i,j} \in L^\infty(\mathbb{R} \times [-T, T]), 1 \leq i, j \leq 2$, and c_1, c_2, c_3, c_4 be real constants. Let $w \in (\mathcal{C}^1([-T, T]; H^s(\mathbb{R})))^2$ be the solution of $\mathcal{L}w = 0$. Assume that $w \equiv 0$ when $x < |t|$ in a neighborhood of $(0, 0)$. Then there exists a neighborhood of $(0, 0)$ in which $w \equiv 0$.

Remark 4.2 If $(\eta, u) \in (\mathcal{C}^1([-T, T]; H^s(\mathbb{R})))^2$ is solution of $\mathcal{L}(\eta, u) = 0$, since

$$\begin{aligned} (1 - c_1 \partial_x^2) \eta_t &= -(a u_{xxx} + c_2 \eta_{xxx} + f_{1,1} \eta_x + f_{1,2} u_x) \\ (1 - c_3 \partial_x^2) u_t &= -(c \eta_{xxx} + c_4 u_{xxx} + f_{2,1} \eta_x + f_{2,2} u_x), \end{aligned}$$

then $(\eta_t, u_t) \in (\mathcal{C}([-T, T]; H^r(\mathbb{R})))^2$ with $r = s$ if $(a = c = c_2 = c_4 = 0)$, $r = s - 3$ if $b = d = 0$ and $r = s - 1$ if not. Therefore the Carleman estimate (3.1) holds if $s \geq 2$, $s \geq 5$ and $s \geq 3$ respectively.

Proof. Let $0 < \delta < 1$, choose $\chi \in \mathcal{C}_0^\infty(B_\delta) \times \mathcal{C}_0^\infty(B_\delta)$ such that $\chi = 1$ in \mathcal{O}_1 a neighborhood of $(0, 0)$ and define $\Phi := \chi w$. It follows that $\Phi \in \mathcal{C}([-T, T]; H^s(\mathbb{R})) \times \mathcal{C}([-T, T]; H^s(\mathbb{R}))$ and $\text{supp } \Phi \subseteq B_\delta \times B_\delta$. We deduce thanks to the preceding corollary, for $\tau > 0$ large enough,

$$\tau^3 \int_{B_\delta} (|\Phi_1|^2 + |\Phi_2|^2) e^{2\tau\Psi} dxdt + \tau^2 \delta^2 \int_{B_\delta} (|\Phi_{1,x}|^2 + |\Phi_{2,x}|^2) e^{2\tau\Psi} dxdt \leq C \int_{B_\delta} |\mathcal{L}\Phi|^2 e^{2\tau\Psi} dxdt. \quad (4.1)$$

The right hand side integral holds on $B_\delta \setminus \mathcal{O}_1$, since $\mathcal{L}\Phi = 0$ in \mathcal{O}_1 .

For $(x, t) \neq 0$ in $\text{supp } \Phi$, we have

$$\Psi(x, t) = (x - \delta)^2 + \delta^2 t^2 < \delta^2 \text{ and } \Psi(0, 0) = \delta^2.$$

Then for $(x, t) \in \text{supp } \mathcal{L}\Phi \subseteq B_\delta \times B_\delta$, there exists $0 < \varepsilon < \delta^2$ such that $\Psi(x, t) \leq \delta^2 - \varepsilon$. On the other hand, we can choose \mathcal{O}_2 a neighborhood of $(0, 0)$ with $\Psi(x, t) > \delta^2 - \varepsilon$ in \mathcal{O}_2 . The inequality (4.1) is then written for all $\tau > 0$

$$C \tau^3 e^{2\tau(\delta^2 - \varepsilon)} \int_{\mathcal{O}_2} |\Phi_1|^2 + |\Phi_2|^2 dxdt \leq e^{2\tau(\delta^2 - \varepsilon)} \int_{B_\delta \setminus \mathcal{O}_1} |\mathcal{L}\Phi|^2 dxdt.$$

Tending τ to infinity implies Φ vanishes in \mathcal{O}_2 . However $w = \Phi$ in $\mathcal{O}_2 \subseteq \mathcal{O}_1$ and $w \equiv 0$ in \mathcal{O}_2 . □

Corollary 4.3

Let $s \geq 5, T > 0, A, B, C \in L^\infty(\mathbb{R} \times [-T, T])$, and c_1, c_2, c_3, c_4 be real constants. Let $w = (\eta, u) \in (\mathcal{C}^1([-T, T]; H^s(\mathbb{R})))^2$ be the solution of

$$\begin{pmatrix} \partial_t - b \partial_{xxt} + A(x, t) \partial_x & a \partial_{xxx} + \partial_x + B(x, t) \partial_x \\ c \partial_{xxx} + \partial_x & \partial_t - d \partial_{xxt} + C(x, t) \partial_x \end{pmatrix} w = 0.$$

We consider the curve $x = \mu(t)$, $\mu(0) = 0$, μ a continuously differential function in a neighborhood of $(0, 0)$. Assume that $w \equiv 0$ when $x < \mu(t)$ in a neighborhood of $(0, 0)$. Then there exists a neighborhood of $(0, 0)$ in which $w \equiv 0$.

Proof. We consider the change of variables $(x, t) \rightarrow (X, T)$ with

$$\begin{aligned} X &= x - \mu(t) + |t| \\ T &= t. \end{aligned}$$

This change of variables provides $W = W(X, T)$ satisfying $W \equiv 0$ when $X < |T|$ in a neighborhood of $(0, 0)$ and $\mathcal{L}W = 0$ with

$$\mathcal{L} := \left(\begin{array}{c} \partial_T + (-\mu'(T) \pm 1)\partial_X - b\partial_{XXT} - b(-\mu'(T) \pm 1)\partial_{XXX} + A\partial_X \\ c\partial_{XXX} + \partial_X \\ \\ a\partial_{XXX} + \partial_X + B\partial_X \\ \partial_T + (-\mu'(T) \pm 1)\partial_X - d\partial_{XXT} - d(-\mu'(T) \pm 1)\partial_{XXX} + C\partial_X \end{array} \right). \quad \square$$

Theorem 4.4

Let $s \geq 5$ and $T > 0$ and $(\eta, u) \in \mathcal{C}([-T, T]; H^s(\mathbb{R})) \times \mathcal{C}([-T, T]; H^s(\mathbb{R}))$ solution of the Boussinesq system. If $(\eta, u) \equiv 0$ in an open subset $\Omega \subseteq (\mathbb{R} \times [-T, T])^2$, then $(\eta, u) \equiv 0$ in the horizontal component of Ω .

Proof. The proof follows [11, 9] or [7] applying the preceding corollary with $A = \rho\eta^{\rho-1}u$, $B = \eta^\rho$ and $C = u^\rho$. Since $s > 1/2$, the functions A, B, C belong to $L^\infty(\mathbb{R} \times [-T, T])$ thanks to the Sobolev embedding. \square

Remark 4.5 These results can be generalized to higher dimensionnal Boussinesq systems:

$$\begin{aligned} \eta_t + \nabla \cdot U + \nabla \cdot (\eta^\rho u) + a\Delta \nabla \cdot U - b\Delta \eta_t &= 0 \\ U_t + \nabla \eta + \frac{1}{\rho+1} \nabla |U|^{\rho+1} + c\Delta \nabla \eta - d\Delta U_t &= 0, \end{aligned}$$

where $\eta = \eta(x_1, \dots, x_n, t)$, $U = (U_1, \dots, U_n)(x_1, \dots, x_n, t)$. We obtain the following Carleman estimates.

Theorem 4.6

We define

$$\mathcal{L} := \left(\begin{array}{c} \partial_t - c_1\Delta \partial_t + c_2\Delta \nabla \cdot + f_{1,1}(x, t)\nabla \cdot \\ c\Delta \nabla + f_{2,1}(x, t)\nabla \\ \\ a\Delta \nabla \cdot + f_{1,2}(x, t)\nabla \cdot \\ \partial_t - c_3\Delta \partial_t + c_4\Delta \nabla \cdot + f_{2,2}(x, t)\nabla \cdot \end{array} \right),$$

where c_1, c_2, c_3, c_4 are constant in \mathbb{R} , $f_{i,j} \in L^\infty(\mathbb{R}^{n+1})$, $1 \leq i, j \leq 2$. Let $\delta > 0$ and $B_\delta := \{(x, t) \in \mathbb{R}^2; \sum_{i=1}^n x_i^2 + t^2 < \delta^2\}$. Then, there exists $C > 0$ such that for all $\Phi = (\Phi_1, \dots, \Phi_{n+1}) \in (\mathcal{C}_0^\infty(B_\delta))^{n+1}$, $\Psi(x, t) = \sum_{i=1}^n (x_i - \delta)^2/n + \delta^2 t^2$ and $\tau > 0$ with

$$\frac{\|f_{i,j}\|_\infty^2}{\tau^2} \ll 1 \text{ for } 1 \leq i, j \leq 2,$$

we have

$$\tau^3 \int_{B_\delta} \left(\sum_{i=1}^{n+1} |\Phi_i|^2 \right) e^{2\tau\Psi} dxdt + \tau^2 \int_{B_\delta} \left(\sum_{i=1}^{n+1} |\nabla \cdot \Phi_i|^2 \right) e^{2\tau\Psi} dxdt \leq C \int_{B_\delta} |\mathcal{L}\Phi|^2 e^{2\tau\Psi} dxdt.$$

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